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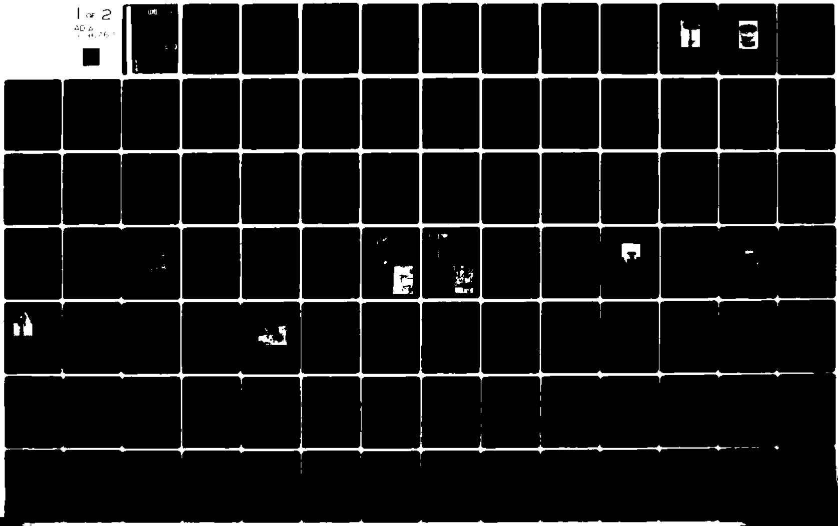

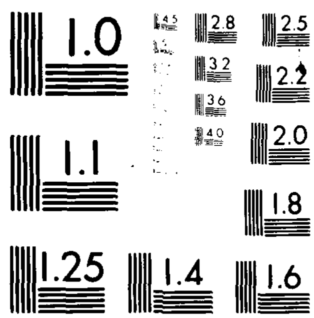

MICROCOPY RESOLUTION TEST CHART

CHARACTERIZATION OF HEAT TRANSFER IN CERAMIC COATED INTERNAL COMBUSTION ENGINES

FINAL REPORT
REPORT ONE

RICHARD G. MURRAY
&
NEIL E. HOECKER

FOR A GRANT PERIOD

FROM 1 JANUARY 1979 TO 31 DECEMBER 1980

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This report outlines the following four areas of interest:

1. The concept of the semiadiabatic engine,
2. The creation of a mathematical model to establish heat transfer and temperature profiles for such engines,
3. The establishment of operational boundary conditions for a semiadiabatic engine, and
4. Discuss the results of an endurance test of ceramic coated engine parts.

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INTRODUCTION

The following document is a final report for Grant Number DAAG29-79-G-0021 funded by the U.S. Army Research Office. This project was started 1 January 1979 and had a duration of two years.

In general, the project was 1) to develop a mathematical model describing heat transfer and temperature characteristics in ceramic coated engine components, 2) measure operational temperatures for such parts with various coating thickness, and 3) continue a previous endurance test of ceramic parts.

THEORETICAL BACKGROUND

PURPOSE

Since the time of Rudolph Diesel, engineers have been trying to develop engines that waste less energy,and thereby develop more power with a given quantity of fuel. It is widely accepted that heat transferred to the cooling system of an engine represents wasted energy. On the other hand, the only practical way known to control engine temperatures is to provide such cooling. In reciprocating engines, the design of pistons and valves has always required careful consideration of temperature as related to component strength and to lubrication. But the cooling necessary to keep these components from overheating not only reduces engine power production, but consumes power to drive the cooling mechanism.

It was recognized by the author that an insulating surface on combustion chamber surfaces offered an approach to the cooling problem by reducing heat transfer to the cooling system and, at the same time, provided lower temperatures of metallic components. Lower metallic temperatures allow redesigning of components for less weight and lower frictional drag.

From a design standpoint, therefore, lower piston temperatures enable lower piston weight, which leads to reduced inertia loadings thus allowing smaller and lighter components such as crankshaft bearings, *connecting rods*, and crankcase structure. The lower temperatures also allow a new freedom in selecting lubricating oils that can reduce viscous drag and windage losses within the crankcase.

A second significant benefit that may result from ceramic coatings is the reduction of the failure rate in valves and pistons, and therefore an increase in engine reliability. While replacement costs for individual engine parts are not unreasonable, the time of failure and the labor required are often critical factors in vulnerable situations.

Engine failure is particularly critical in military applications. Often military engines are destroyed by a combination of operational factors in or near a combat zone. For example, it is not uncommon for the operator to refuel with any available fuel and then operate the vehicle at peak power for extended time intervals. Either a spark ignition (S-I) or a compression ignition (C-I) engine operated in this mode will develop severe knock. Knock, in turn, dramatically increases convection boundary layer heat transfer which may raise valve and piston temperature to a point of failure.

Figure 1, following, is a photograph illustrating a diesel exhaust valve failure caused by excessive thermal stress (hoop stress failure). A more common failure occurs when the valve head separates from the stem ("valve swallowing"), after high temperature stress and erosion. This second failure mode usually occurs at high power and high rpm conditions resulting in substantial, if not complete, engine destruction.

Two examples of piston damage resulting from high temperature operation are shown in figures 2 and 3. Both are caused by knock induced heat transfer. The second, however, was aggravated by preignition at the spark plug center electrode.

Insulated coatings are expected not only to economically eliminate all of the above types of engine failure, but also, to increase engine efficiency and reduce overall engine weight.

Based on the information above, it appears that one small breakthrough in controlling heat transfer offers the opportunity for major engine improvement. For these reasons, it is highly desirable to gain a better

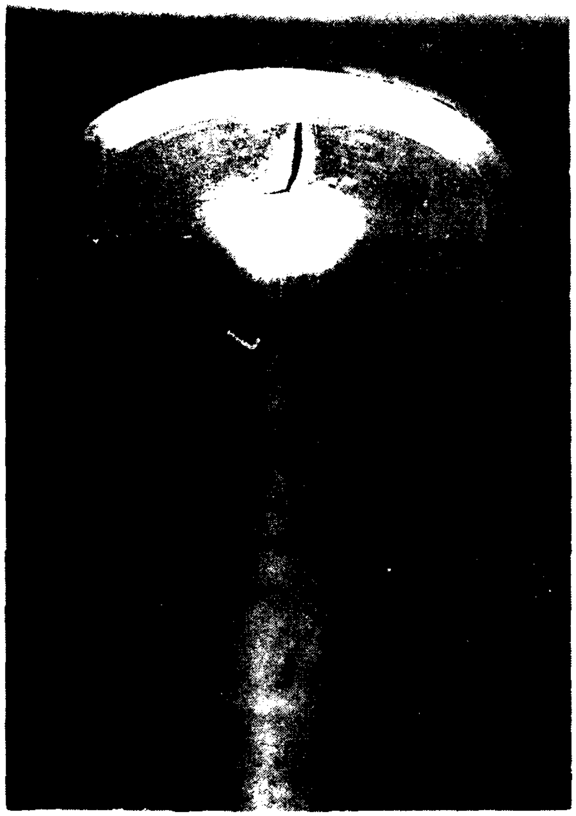

Figure 1: Valve Failure

Figure 2: Piston Failure Knock

Figure 3: Piston Failure Preignition

understanding of how heat is transferred in ceramic coated internal combustion engine parts.

PREVIOUS WORK

Shortly after the principal investigator realized the possible benefits of insulated combustion chamber surfaces, he wrote a mathematical model to investigate coated engine performance. The model did predict both increased efficiency and lower component temperatures. Following analysis of the model, he participated in two engine test programs involving coated parts.

The first engine test program was a multicylinder test at the Johnson Space Center in Houston. The major outcome of this test was proof that plasma sprayed ceramic coatings could endure the torturous environment of an engine combustion chamber for extensive periods of time without significant deterioration.

The second test program was a U.S. Army funded study at Oklahoma State University which investigated engine performance characteristics. Both spark ignition (S-I) and compression ignition (C-I) performance were investigated at various compression and equivalence ratios. These tests incorporate a thin coating (0.025") of yttrium stabilized zirconium oxide on the piston, valves, and cylinder head surfaces of a Cooperative Fuel Research (CFR) engine. In addition, tests were undertaken to investigate how various catalysts applied to these coatings will affect combustion. The details of this project are found in the final report, project No. P-14099-E entitled "Improved Engine Performance Through Heat Transfer Control", available by contacting the U.S. Army Research Office, Research Triangle, North Carolina.

CERAMIC COATINGS

Several ceramic substances have been developed in the last few years that exhibit excellent insulating properties. These substances can be sprayed on metal surfaces by flame or plasma methods and also can be applied by a device known as a detonation gun. Some properties of various coatings and metals follow in table 1.

To reduce heat transfer in an engine cylinder, two physical coating properties are of prime importance. First, the material must adhere to the metallic subsurface without any significant interface stress over a wide range of temperature. This necessitates that the coefficient of thermal expansion of the coating should be of the same order of magnitude as the base structure. Second, it should have as low a thermal conductivity as possible in order to effectively control heat transfer. Properties of lesser importance are specific heat, compressive strength, and adherence. Of all the coating materials investigated, yttrium stabilized zirconium oxide best fits the requirements for engine combustion chamber insulation.

Adherence of plasma and flame sprayed zirconium oxide to cast iron and aluminum surfaces is, however, in some cases not good, and coating separations will occur if proper techniques are not observed. Metallic surfaces must be clean and free of oil prior to coating. In some cases, it may be necessary to preheat cast iron surfaces to expel residual oil from machining process. To promote good bonding, it is suggested that metallic surfaces be grit blasted and given a flash coat of nickel aluminate before application of the zirconium oxide coating.

PROJECT SCOPE

The preceding section has outlined the historical use of ceramic coatings to improve engine performance and to make engines more tolerant of low grade fuel. This project was undertaken to establish a data base to assist design engineers in the adoption of ceramic coatings. To achieve this goal, a two year project was implemented to:

1) create a mathematical model that can predict piston and exhaust valve heat transfer as a function of engine design parameters and coating characteristics,

2) establish operational temperature profiles for coated pistons and valves, and

3) an additional assignment for this project was to

Table 1

PHYSICAL PROPERTIES

Material	Thermal Conductivity	Coefficient of Expansion	Bulk Density	Specific Heat	Melting Temperature
	$\frac{BTU}{hr\ ft\ °F}$	$\frac{in}{in\ °F} \times 10^{-6}$	$\frac{gm}{cm^3}$	$\frac{BTU}{\#\ °F}$	°F
	$(\frac{cal}{Sec\ cm\ C})$	$(\frac{cm}{cm\ C} \times 10^{-6})$		$(\frac{cal}{cm\ C})$	(°C)
Zirconium Oxide	0.67 (2.77×10^{-3})	5.4 (3.0)	5.2	0.175 (6.018)	4500 (2482)
Aluminum Oxide	1.58 (0.01)	4.1 (2.28)	3.3	0.28 (0.028)	3600 (1982)
Chrome Oxide	1.50 (0.01)	5.0 (2.78)	4.6	0.20 (0.020)	3000 (1649)
Aluminum	120 (0.50)	13.0 (7.22)	2.7	0.22 (0.022)	1220 (660)
Cast iron	27 (0.11)	6.5 (3.61)	7.88	0.11 (0.011)	2800 (1538)

Source: "Rokide Ceramic Spray Coating",
The Norton Company, 1961.

continue an endurance test for ceramic coated engine parts. Prior to the start of this project an engine had undergone 1000 hours of operation simulating highway conditions. A second 1000 hours of operation was established as a third goal of this project.

THE MATHEMATICAL MODEL

GENERAL

Engine pistons and exhaust valves are three dimensional objects having configurations that can typically be portrayed by figures 4 and 5, respectively.

The piston and valve combustion chamber surfaces receive a cyclic heat input during each combustion, expansion and exhaust process. This heat flow depends primarily on the power loading of the engine and the combustion characteristics. These same surfaces are also subjected to a cyclic cooling during the intake and compression processes. The cooling tendency varies mainly with air-fuel ratio and engine power level.

Primary piston cooling is through the piston rings and heat transfer to lubricating oil, both being somewhat cyclic in nature.

Exhaust valve heat rejection occurs primarily to the valve seat and valve guide. Both of these sinks change characteristics with time and therefore are transient in nature.

While both the piston and exhaust valve are transient heat transfer devices, they may be treated as steady state for practical purposes. The insulating effect of a ceramic surface tends to isolate the core metal structure from temperature fluctuations, in other words, it is believed that the interior temperature of both such pistons and valves is controlled more by the constant temperature sink and the physical properties of the metal than by the cyclic heat load. This theory was verified in the laboratory; details and test data confirming this will be presented later.

As seen in figure 5, the exhaust valve is symmetrical and can, therefore, be treated as a two dimensional heat transfer body.

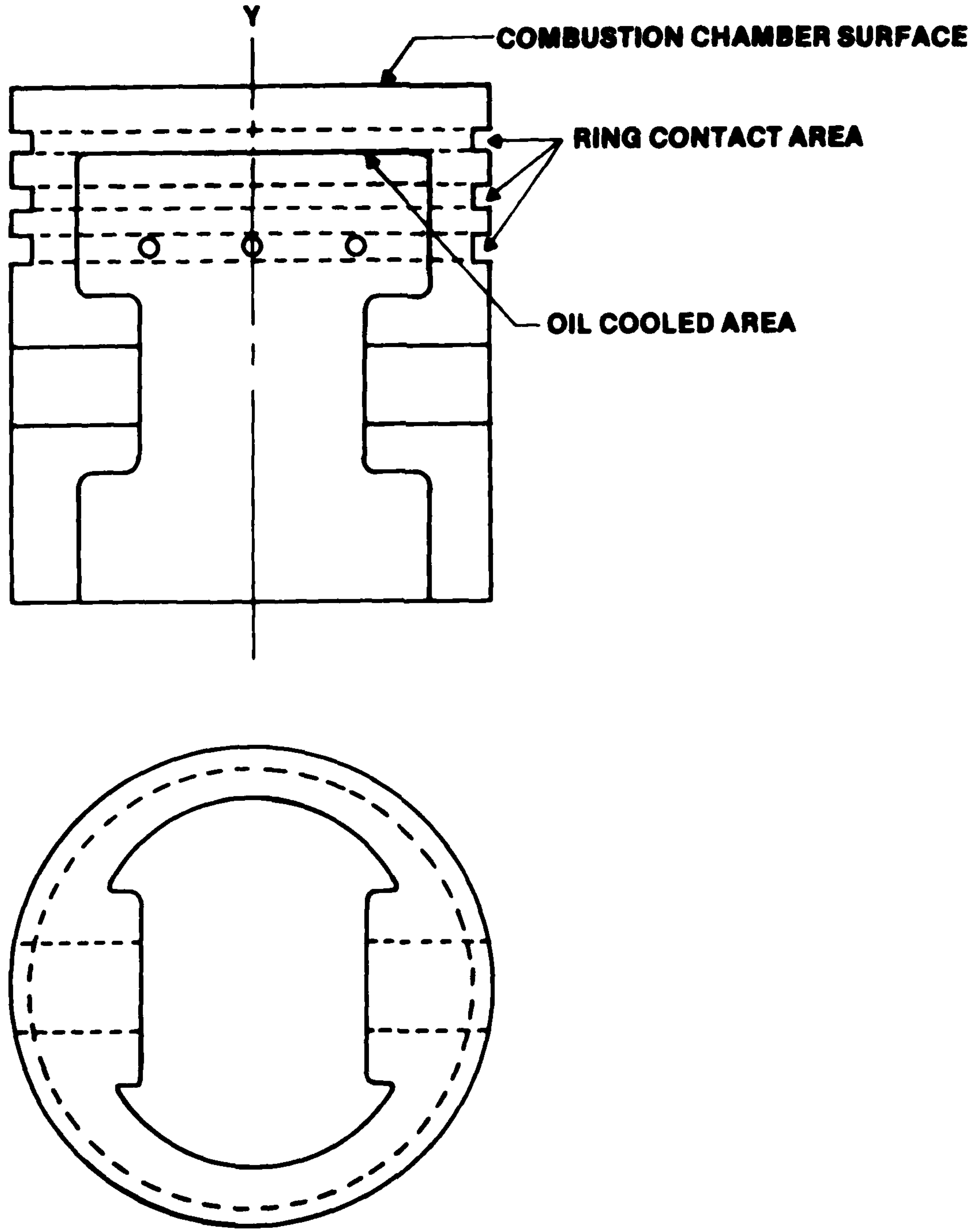

Figure 4: Typical Piston Configuration

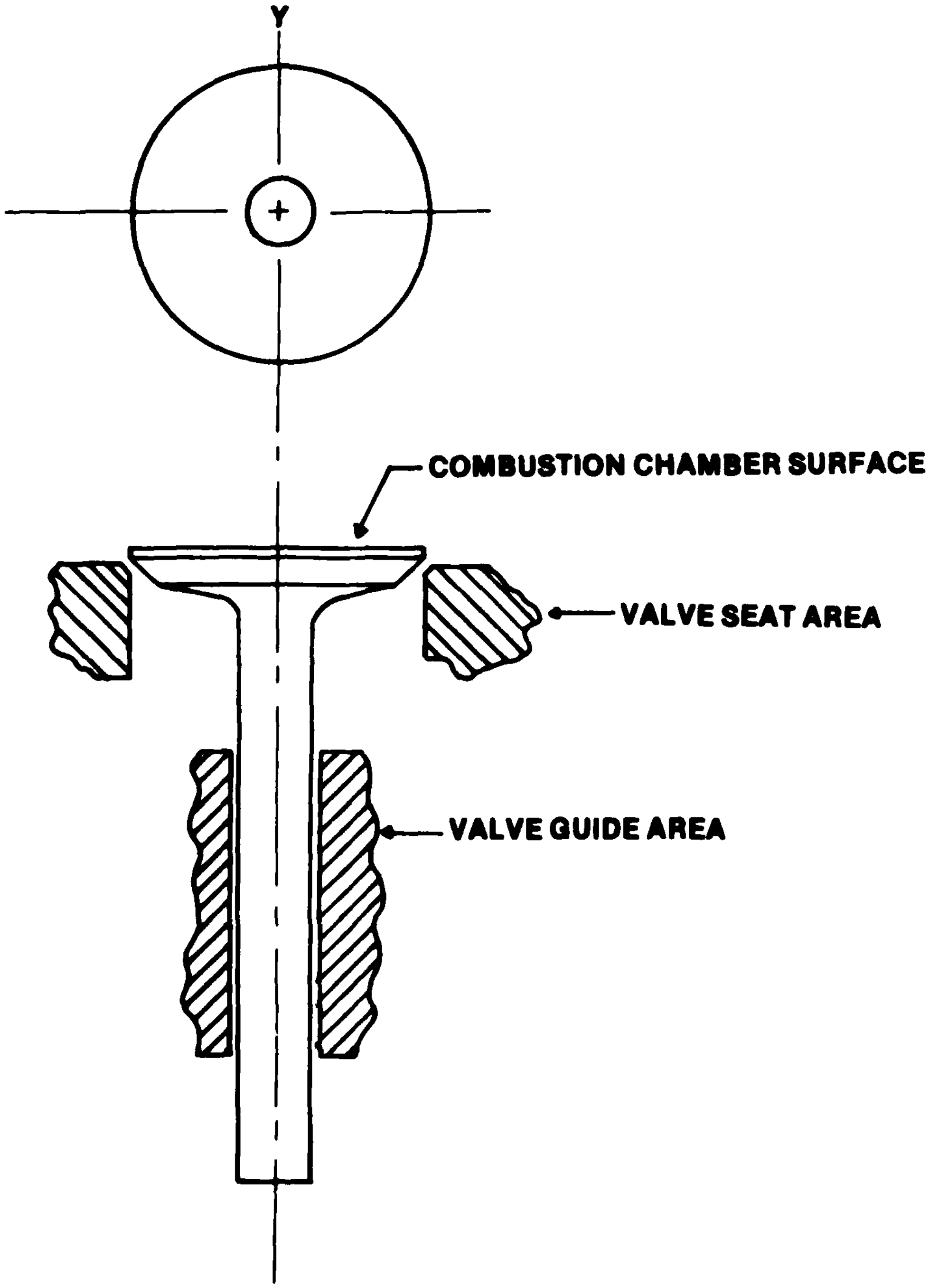

Figure 5: Typical Valve Configuration

The piston is also basically symmetrical with the exception of the wrist pin boss. This boss, however, is typically located well below the ring area and, therefore, is usually considered to have little contribution to the overall piston heat transfer. Studies indicate that most heat transfer takes place in the upper ring area and on the top portion of oil cooled lower piston crown (1-7)* and, therefore, confirm that the wrist pin boss may be treated as an insignificant factor in heat transfer. This reasoning allows one to treat piston and valve heat transfer as a two dimensional, steady state problem.

If one first examines the general relationships for three dimensional heat transfer in an element as shown in figure 6, he can determine the heat transfer (8) in each of the three directions from

$$q_x = -KA \left(\frac{\partial T}{\partial x}\right) \tag{1}$$

where $A = dy\ dx$,

$$q_y = -KA \left(\frac{\partial T}{\partial y}\right) \tag{2}$$

where $A = dx\ dz$,

and

$$q_z = -KA \left(\frac{\partial T}{\partial z}\right) \tag{3}$$

where $A = dx\ dy$,

where T is temperature, K is thermal conductivity, and q is heat transfer. The three dimensional heat conduction equation for homogeneous materials without interior heat generation is:

*References are at the end of narrative.

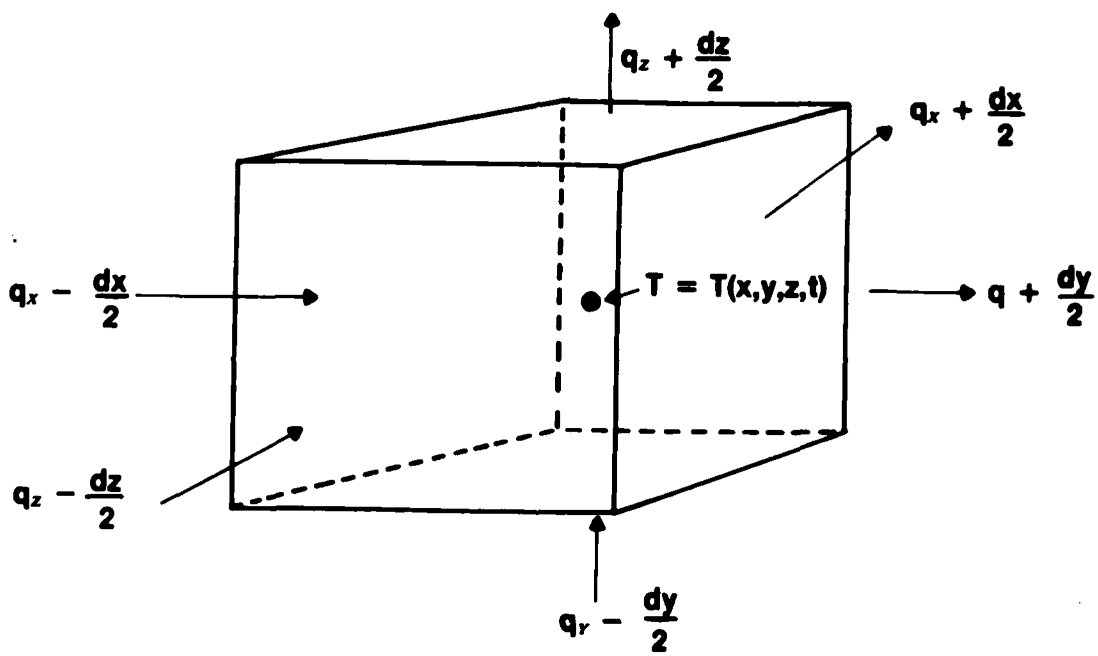

Figure 6: Elemental Heat Transfer

$$\frac{\partial T}{\partial t} = K \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) , \qquad (4)$$

where t is time.

For steady state conditions $\frac{\partial T}{\partial t} = 0$ and equation 4 becomes

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0. \qquad (5)$$

The above is known as Laplace's Equation and is often written as $\Delta T = 0$. If Laplace's Equation is transformed to cylindrical coordinates by substituting $x = r \cos\theta$; $y = r \sin\theta$; and $z = z$; and if cylindrical symmetry is assumed

$$\left(\frac{\partial T}{\partial \theta} = 0 \right),$$

the equation reduces to:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = 0 . \qquad (6)$$

Since symmetry is justified in this study, equation 6 becomes the governing equation for pistons and exhaust valves. Figure 7 illustrates this application for a piston.

To solve the heat transfer problem for such components, one must solve Laplace's Equation having certain boundary conditions known. A finite difference approach to this solution has been selected and will follow.

FINITE DIFFERENCE METHOD

Laplace's Equation has a unique solution for each set of boundary conditions specified. However, analytical solutions have been worked out only for problems with certain special geometries and boundary conditions. The following solution will be to overlay the cross section of the piston (and valve) with a grid of points (r, z) and to

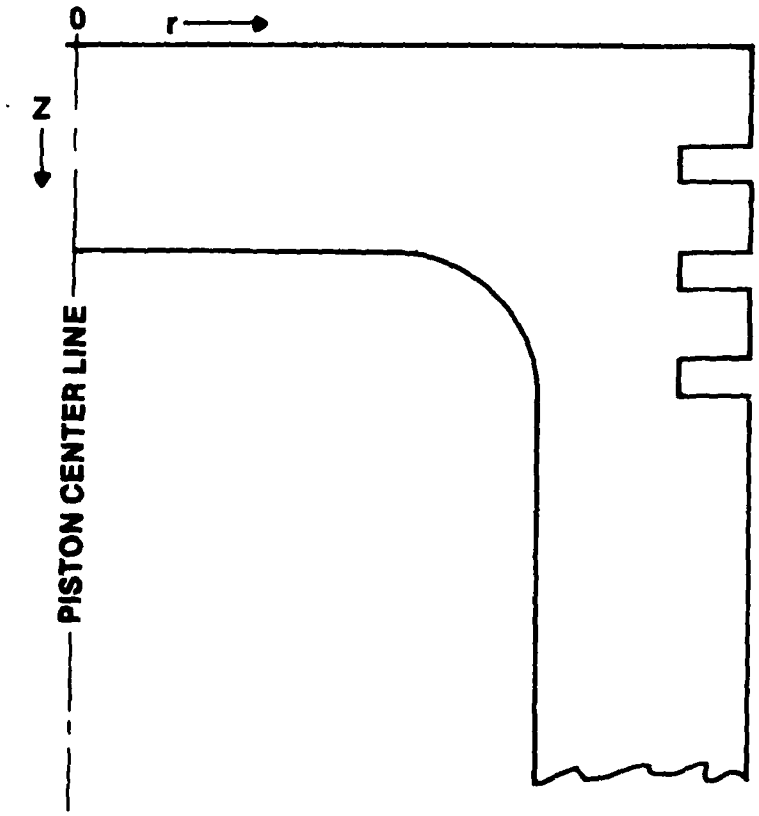

Figure 7: Piston Cross Section

find the temperature at each point numerically. A typical grid is as follows in figure 8.

The numerical approach first approximates the partial derivatives at each point by using a finite difference or

$$\frac{\partial T}{\partial r}(r,z) \doteq \frac{1}{2h_1}\left[T(r+h_1,z) - T(r-h_1,z)\right] \tag{7}$$

$$\frac{\partial^2 T}{\partial r^2}(r,z) \doteq \frac{1}{h_1^2}\left[T(r+h_1,z) + T(r-h_1,z) - 2T(r,z)\right] \tag{8}$$

and

$$\frac{\partial^2 T}{\partial z^2}(r,z) \doteq \frac{1}{h_2^2}\left[T(r,z+h_2) + T(r,z-h_2) - 2T(r,z)\right] \tag{9}$$

where h_1 is the horizontal grid spacing and h_2 is the vertical grid spacing.

Equation 6 now becomes:

$$\frac{1}{h_1^2}\left[T(r+h_1,z) + T(r-h_1,z) - 2T(r,z)\right] + \frac{1}{rh_1}\left[T(r+h_1,z) - T(r-h_1,z)\right] +$$

$$\frac{1}{h_2^2}\left[T(r,z+h_2) + T(r,z-h_2) - 2T(r,z)\right] \doteq 0. \tag{10}$$

For the center line element $(r = 0)$ a slightly different approximation is needed. As

$$r \rightarrow 0, \quad \frac{1}{r}\frac{\partial T}{\partial r} \rightarrow \frac{\partial^2 T}{\partial r^2}$$

so the governing equation becomes:

$$2\frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} = 0. \tag{11}$$

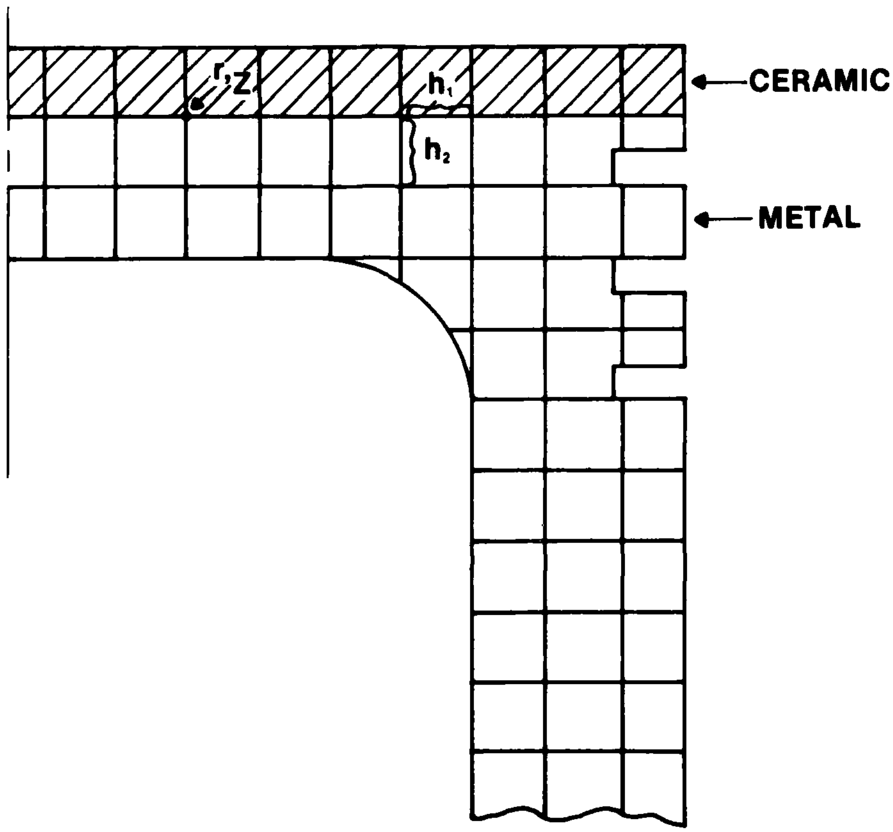

Figure 8: Piston Grid Network

The above can be simplified if $h_1 = h_2$ and the following substitutions are made:

$$T_{(r + h,z)} = T_{i + 1, j}$$

$$T_{(r - h, z)} = T_{i - 1, j}$$

$$T_{(r, z + h)} = T_{i, j + 1}$$

The following finite difference equations exist for all points except where r = 0:

$$0 = -4\, T_{i,j} + T_{i,j+1} + T_{i, j-1} + \left(1 - \frac{h}{2r}\right) T_{i-1,j} +$$

$$\left(1 + \frac{h}{2r}\right) T_{i+1,j} \tag{12}$$

For center line points, (r = 0), the corresponding finite difference equation is:

$$0 = -6\, T_{i,j} + 2T_{i-1,j} + 2T_{i+1,j} + T_{i, j+1} + T_{i,j-1} \tag{13}$$

which by symmetry yields:

$$0 = -6\, T_{i,j} + 4\, T_{i+1, j} + T_{i, j+1} + T_{i,j-1} \tag{14}$$

MODELING THE CERAMIC COATING

Special consideration must be given to the points where the ceramic coating meet the metallic piston (valve) surface. Linear equations for these points are obtained by assuming a one dimensional flow across the ceramic and using the heat equation:

$$q = -KA \frac{\partial T}{\partial z} \quad . \tag{15}$$

This is illustrated in figure 9.

To obtain an equation involving T_1, T_2, and T_3 one can calculate the heat flowing through the interface area (A) both from the ceramic and the metal.

$$q = -K_c A \left(\frac{T_1 - T_2}{d} \right) \tag{16}$$

and

$$q = -K_m A \left(\frac{T_2 - T_3}{h_2} \right) \tag{17}$$

Equating these equations yields:

$$\frac{K_c A}{d} (T_1 - T_2) = \frac{K_m A}{h_2} (T_2 - T_3) \tag{18}$$

or

$$T_2 = \frac{h_2 K_c T_1 + d K_m T_3}{h_2 K_c + d K_m} \tag{19}$$

This gives a linear equation for each grid point of contact from the ceramic and the metal.

COMBINED SOLUTION

An equation now exists for the temperature at each interior point (r,z) and the surrounding grid points. The n-equations involving n-unknowns have been generated. These equations can be solved directly by Gaussian elimination or by an iterative process like the Gauss-Seidel method. In the Gauss-Seidel method the temperature at one point (r,z) is solved in terms of the temperatures at all surrounding grid points.

The result is a temperature distribution throughout the piston or valve.

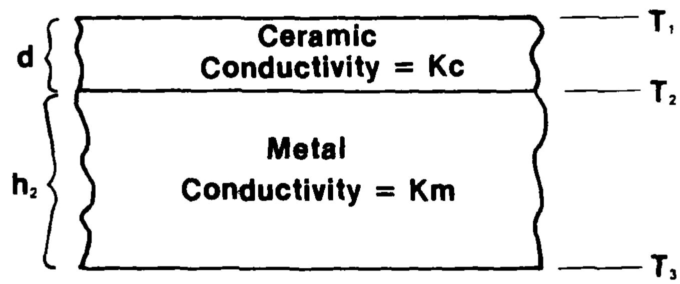

Figure 9: Ceramic Metal Interface

DETERMINATION OF THERMAL CONDUCTIVITY

The thermal conductivity of each substance involved must be accurately known over a range of temperatures before any mathematical model can be completed. The temperature dependency of aluminum, steel, cast iron and other metals is well known and documented over a reasonable range. Plasma sprayed zirconium oxide, however, does not have a widely accepted conductivity at the temperatures involved by engine components.

Before completion of a mathematical model, therefore, it was necessary to determine such values. Samples of steel were machined to a standard sample size. Several of these were plasma sprayed with yttrium stabilized zirconium oxide using the same techniques as for engine parts. These samples, as well as uncoated specimens, were sent to the Thermophysical Properties Research Laboratory at Purdue University for evaluation. The results of this analysis were incorporated in the following computer model and are presented as appendix 1.

THE COMPUTER PROGRAM

The preceding section has illustrated a mathematical method to describe the temperature at all interior points for engine parts that encounter two dimensional (r,z), steady state heat transfer.

A major portion of this effort was to incorporate these equations into a computer program that would give engineers a tool for designing engines that incorporate ceramic coated pistons and valves. The following section outlines the details of the resulting program.

Figure 10 details the step by step procedure to input component details into the program and to acquire the resulting temperature profiles and heat transfer.

To implement the program, a grid must be established similar to the one following in figure 11. The temperature at each solid dot is needed in the data.

The first data card contains the number of rows, the number of columns, the number of data sets, the conductivity of the coating, the conductivity of the metal, and the acceptable iteration limit. A data

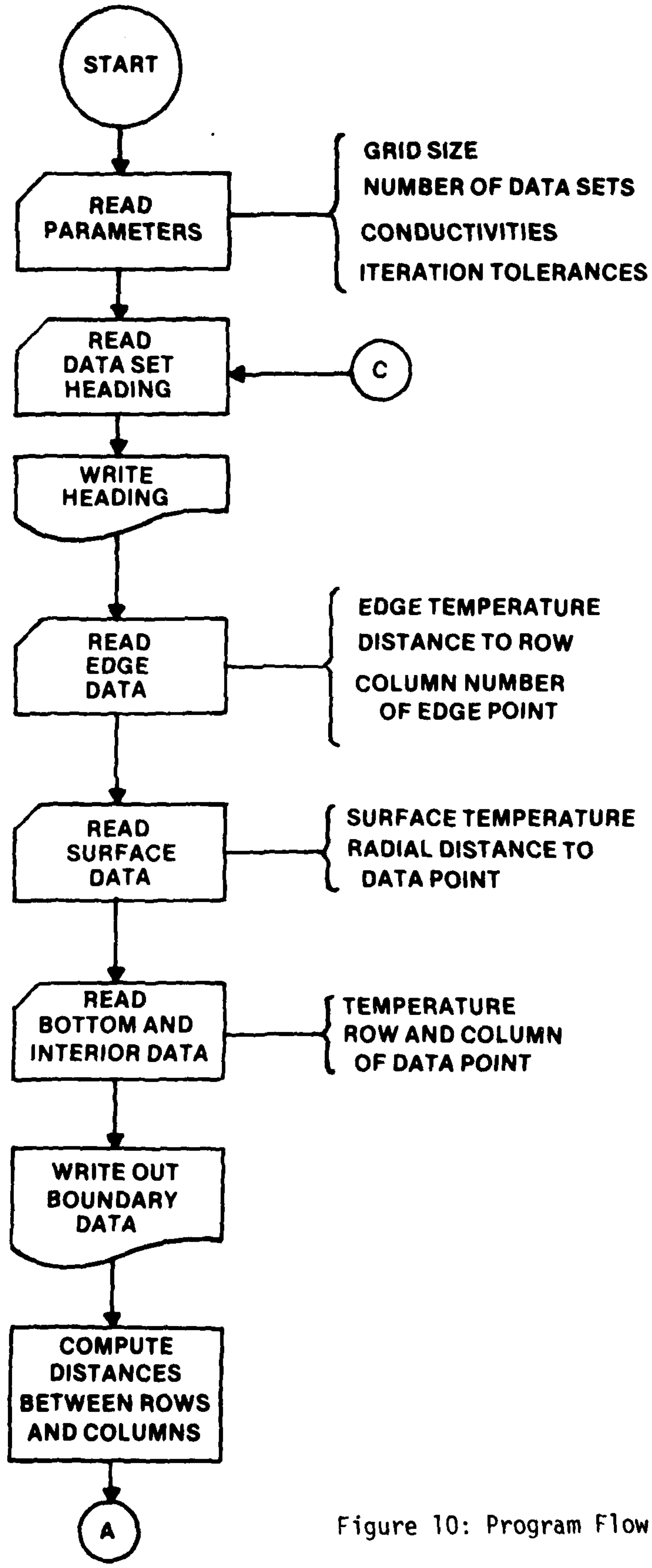

Figure 10: Program Flow Chart

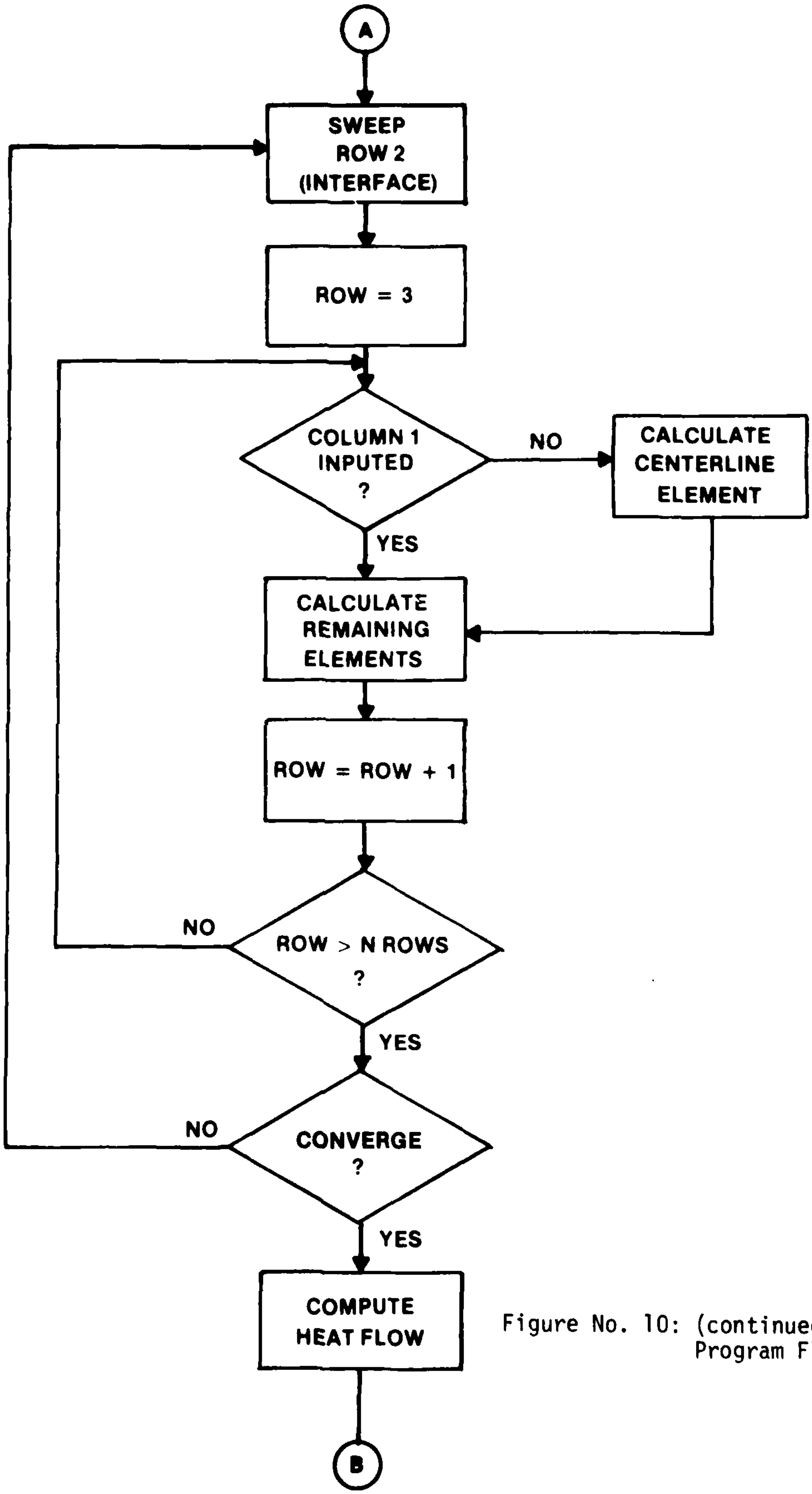

Figure No. 10: (continued)
Program Flow Chart

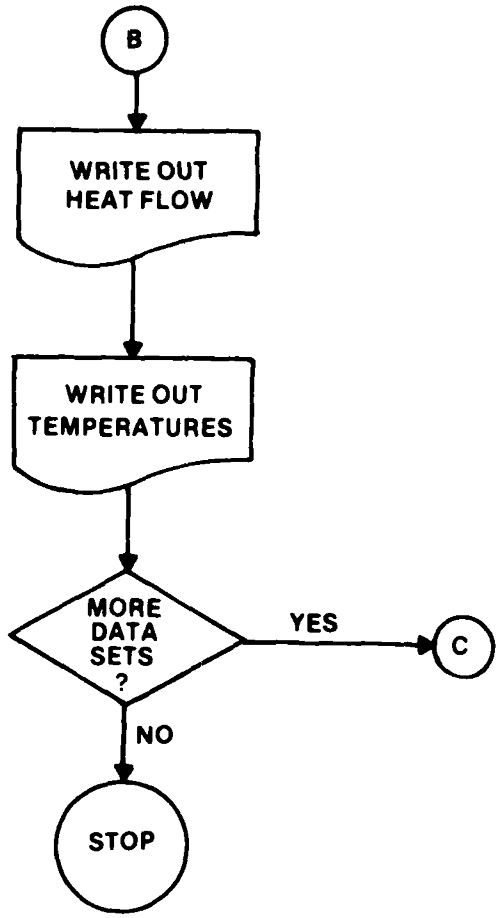

Figure No. 10: (continued)
Program Flow Chart

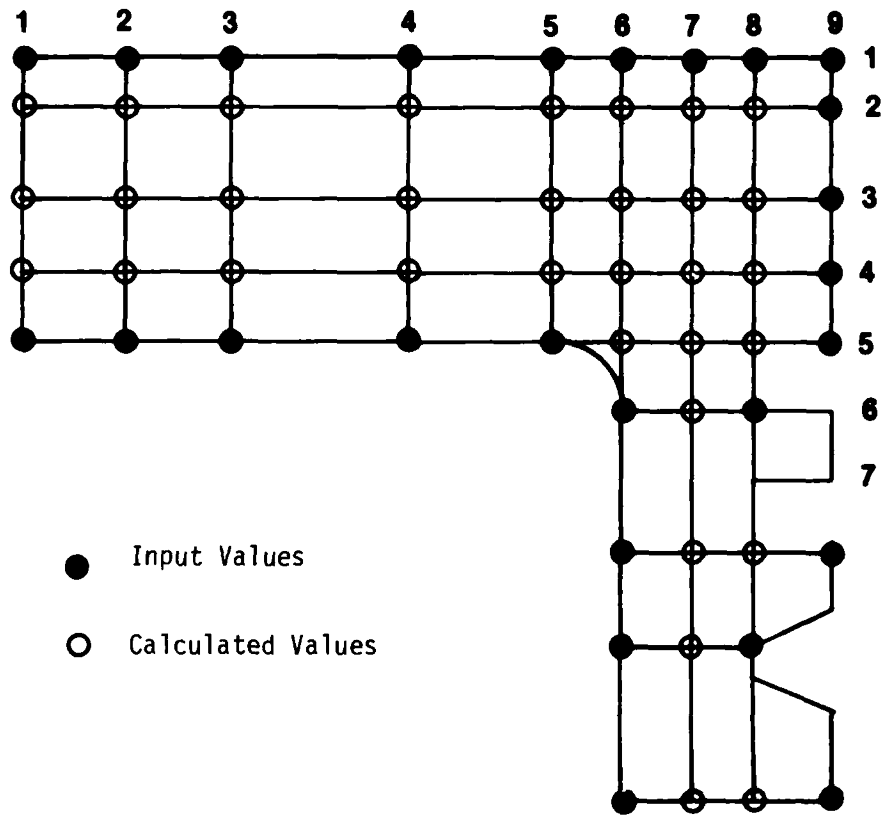

Figure 11: Piston Grid Points

set consists of the boundary temperatures for the test of a particular configuration. This information applies to all the data sets that follow. Each data set is composed of four sections. The first section is a single card which contains the label for the data set. The second section contains the temperatures along the outer edge. For each row there is one card which contains the edge temperature, and the dimensions to the point from the top and perimeter of the component by column number. The vertical dimension is recorded in inches of depth while the horizontal dimension is stated only by column number. The format for these cards is (F10.3, F9.3, I2). The temperature is recorded in degrees Fahrenheit (in agreement with the units on thermal conductivity) and the distance is recorded in inches.

The third section of the data set is composed of the surface temperatures and column spacing. For each column in the grid, a surface temperature and distance from the center of the piston valve is given. The format is (2F10.3). Again, the temperature is in degrees Fahrenheit and the radial location is recorded in inches.

The last section of the boundary data contains the temperatures on the bottom and interior wall (crankcase surface) for the piston and for the tulip on the valve. Each data card in this section contains a row, column, and temperature of a boundary point not covered in either section two or three.

A data card of this type with row = 20 and column = 20 is needed to signal the end of the data for each set. The format for these cards is (2I5,F10.3).

Note that the distance between rows 1 & 2 corresponds to the coating thickness. As written, this program solves for 9 rows and 9 columns. This quantity can be increased by changing the format and programming for the last data card of the fourth data section.

The output of this program contains a representation of the boundary values inputed into the program, a final temperature for each grid point, and the rate of heat flow vertically from the surface of the piston (or valve) in BTU/hr.

A card by card listing of the final version of the program follows:

(see next page)

A sample set of data cards used to test the program is listed below:

(see following pages)

These data cards produce an output as follows:

(see following pages, table 4-Program Output).

The following is a series of two profiles, each of which roughly outlines the geometry of the part being tested. The top profile tabulates inputed temperatures and the respective location of each point. The top outside points has values of r = 1.63 inches, z = 0.00 inches and t = 280 °F. Interior points are unknown at the time of data input and are therefore printed as zero.

The calculated heat flow through the top surface is written between the two profiles and in this sample case equals 366.7 BTU per hour.

The second (lower) profile displays the calculated temperatures at interior points as well as the input data from the top profile. In both profiles, the area shaded by the letter "U" represents the crankcase environment.

The program gives one the ability to calculate heat flow and the temperature and distribution for any coated engine part with two dimensional heat flow.

OPERATIONAL TEMPERATURES

GENERAL

To design engines incorporating ceramic coated parts, it is desirable not only to have a mathematical model that calculates heat flow and interior temperatures, but also one needs information about actual surface temperatures as they relate to engine operating conditions. In addition

```
CCCC                                                                    AR000001
CCCC         THIS PROGRAM COMPUTES THE HEAT FLOW FROM THE SURFACE AR000002
CCCC      OF A VALVE OR PISTON COATED WITH AN INSULATING                 AR000003
CCCC      SUBSTANCE SUCH AS A CERAMIC MATERIAL.  THE                     AR000004
CCCC      TEMPERATURE AT  THE INTERIOR GRID POINTS IS ALSO               AR000005
CCCC      DETERMINED.                                                    AR000006
CCCC                                                                     AR000007
CCCC                                                                     AR000010
CCCC                MAJOR VARIABLES USED                                 AR000020
CCCC                                                                     AR000030
CCCC      TEMP(I,J)    -   TEMPERATURE AT GRID POINT I,J.               AR000040
CCCC                                                                     AR000050
CCCC      NROWS        -   NUMBER OF ROWS IN GRID.                       AR000060
CCCC                                                                     AR000080
CCCC      NCOLS        -   NUMBER OF COLUMNS IN GRID.                    AR000090
CCCC                                                                     AR000100
CCCC      NRUNS        -   NUMBER OF DATA SETS TO BE RUN.                AR000110
CCCC                                                                     AR000120
CCCC      XKINSU       -   CONDUCTIVITY OF THE COATING.                  AR000130
CCCC                                                                     AR000140
CCCC      XKMETL       -   CONDUCTIVITY OF THE METAL.                    AR000150
CCCC                                                                     AR000160
CCCC      AVGTOL       -   ALLOWABLE AVERAGE TEMPERATURE CHANGE          AR000170
CCCC                       IN DEGREES F BETWEEN ITERATIONS.              AR000175
CCCC                                                                     AR000180
CCCC      MAXTOL       -   ALLOWABLE TEMPERATURE CHANGE AT ANY           AR000190
CCCC                       GRID POINT PER ITERATION.                     AR000195
CCCC                                                                     AR000210
CCCC      TEDGE(I)     -   TEMPERATURE ON THE EDGE AT ROW I.             AR000220
CCCC                                                                     AR000230
CCCC      ZDIST(I)     -   VERTICAL DISTANCE TO ROW I.                   AR000240
CCCC                                                                     AR000250
CCCC      RDIST(I)     -   DISTANCE FROM CENTER TO COLUMN I.             AR000260
CCCC                                                                     AR000270
CCCC      DZ(I)        -   DISTANCE BETWEEN ROW I AND ROW I+1.           AR000280
CCCC                                                                     AR000290
CCCC      DR(I)        -   DISTANCE BETWEEN COLUMNS I AND I+1.           AR000300
CCCC                                                                     AR000310
CCCC      JFIRST(I)    -   COLUMN NUMBER OF FIRST CALCULATED GRID        AR000320
CCCC                       POINT IN ROW I.                               AR000321
CCCC                                                                     AR000324
CCCC      NFIXED       -   NUMBER OF POINTS IN ROW I THAT ARE NOT        AR000325
CCCC                       COMPUTED.                                     AR000326
CCCC                                                                     AR000330
CCCC      XNPTS        -   NUMBER OF COMPUTED POINTS IN GRID.            AR000340
CCCC                                                                     AR000350
CCCC      Q            -   VERTICAL RATE OF HEAT FLOW.                   AR000360
CCCC                                                                     AR000370
CCCC      OMEGA        -   ACCELERATION CONSTANT IN THE RELAXATION.      AR000380
CCCC                       (FIXED AT 1.5)                                AR000385
CCCC                                                                     AR000390
      COMMON      TEMP,RDIST,ZDIST,ABSDIF,DIFSUM,OMEGA,DIFMAX            AR000400
      COMMON LAST,NROWS,NCOLS,JFIRST                                     AR000410
      DIMENSION HEAD(20)                                                 AR000420
      DIMENSION TEMP(20,20), TEDGE(20), ZDIST(20), RDIST(20), LAST(20)   AR000430
      DIMENSION DZ(20),DR(20), DIFF(10), JFIRST(20), NFIXED(20)          AR000440
      MAXITS = 100                                                       AR000450
      NFIXED(20) = 0                                                     AR000460
CCCC                                                                     AR000470
```

Table 2: Program

```
CCCC
CCCC     READ PROGRAM PARAMETERS
      READ(5,10) NROWS,NCOLS,NRUNS,XKINSL,XKMETL,AVGTOL,DIFTOL
   10 FORMAT(3I5,5X,4F10.7)
      WRITE(6,20) XKINSU
      WRITE (6,30) XKMETL
      WRITE(6,40) AVGTOL
      WRITE(6,50) DIFTOL
   20 FORMAT('1  THE THERMAL CONDUCTIVITY FOR THE INSULATION IS',F9.5)
   30 FORMAT('0  THE THERMAL CONDUCTIVITY FOR THE METAL IS ',F9.5)
   40 FORMAT('0 THE TOLERANCE FOR CHANGE IN AVG ELEMENT TEMP'
     *,' BETWEEN ITERATIONS IS ',F9.5)
   50 FORMAT('0  THE TOLERANCE FOR MAXIMUM CHANGE IN TEMPERATURE IS ',
     * F9.5)
      WRITE(6,60)
   60 FORMAT('0  NOTE  THE UPPER LEFT HAND CORNER IS THE TOP CENTER'
     * ,' OF THE PISTON OR VALVE.')
      OMEGA = 1.5
      NRM1=NROWS -1
      NCM1 = NCOLS -1
      DO 270 LOOP = 1,NRUNS
      READ(5,70)  (HEAD(KK),KK=1,20)
   70 FORMAT(20A4)
      WRITE(6,80)  (HEAD(KK),KK=1,20)
   80 FORMAT(1H1,//    ,10X,20A4)
CCCC
CCCC     READ THE DATA FROM THE PISTON EDGE.
CCCC
      READ(5,90)  (TEDGE(I),ZDIST(I),LAST(I),I=1,NROWS    )
   90 FORMAT (F10.3,F9.3,I2)
CCCC
CCCC     INCORPORATE EDGE DATA INTO TEMPERATURE MATRIX.
CCCC
      DO 100 I=2,NROWS
      J= LAST(I)
      TEMP(I,J) = TEDGE(I)
  100 CONTINUE
CCCC
CCCC     READ DATA FROM PISTON SURFACE.
CCCC
      READ(5,110)  (TEMP(1,J),RDIST(J),J=1,NCOLS)
  110 FORMAT(2F10.3)
CCCC
CCCC     READ REMAINING DATA IF ANY
CCCC
      DO 120 I=1,NROWS
      JFIRST(I) = 1
      NFIXED(I) = 0
  120 CONTINUE
CCCC
CCCC     THE LAST CARD READ SHOULD HAVE I=20 AND J=20.
CCCC
  130 READ(5,140) I,J,T
  140 FORMAT(2I5,F10.2)
      TEMP(I,J) = T
      JFIRST(I) = J+1
      NFIXED(I) = NFIXED(I) +1
      IF (I+J .LT. 40) GO TO 130
CCCC
CCCC     INITIALIZE THE INTERIOR OF THE TEMP MATRIX.
```

Table 2: Continued

```
CCCC
      XNPTS = 0.0
      DO 150 I=2,NROWS
      K=LAST(I) -1
      JT= JFIRST(I)
      DO 150 J=JT,K
      TEMP(I,J) =0.0
      XNPTS = XNPTS + 1.0
  150 CONTINUE
      CALL OUTPUT
CCCC
CCCC     INITIALIZE COUNTERS.
CCCC
      DIFMAX = 0.0
      DIFSUM = 0.0
CCCC
CCCC     COMPUTE THE DISTANCES BETWEEN ROWS.
CCCC
      DO 160 I=1,NRM1
      DZ(I) = ZDIST(I+1) -ZDIST(I)
  160 CONTINUE
      DZ(NROWS) = DZ(NRM1)
      THICK = DZ(1)
CCCC
CCCC     COMPUTE DISTANCE BETWEEN COLUMNS.
CCCC
      DO 170 J=1,NCM1
      DR(J) = RDIST(J+1) - RDIST(J)
  170 CONTINUE
CCCC
CCCC     BEGIN RELAXATION SWEEPS.
CCCC
      DO 260 M=1,MAXITS
CCCC
CCCC         SWEEP ROW 2 (WHERE THE INSULATION MEETS THE METAL).
CCCCC
      DO 180 J=1,NCM1
      D2 = DZ(2)
      D1 = DZ(1)
      HOLD = (D2*XKINSU*TEMP(1,J)+D1*XKMETL*TEMP(3,J))/(D2*XKINSU +
     *   D1*XKMETL)
      CALL RELAX(2,J,HOLD)
  180 CONTINUE
CCCC
CCCC     SWEEP ROWS 3 TO NROWS
CCCC
CCCC     SET UP DUMMY ROW TO SIMULATE INSULATION AT BOTTOM OF CROWN.
CCCC
      JEND = LAST(NROWS-1)
      JT = JFIRST(NROWS)
      DO 190 J=JT,JEND
  190 TEMP(NROWS+1,J) = TEMP(NROWS-1,J)
      DO 220 I=3,NROWS
      DA= DZ(I-1)
      DB=DZ(I)
      CONAB = DA*DB*(DA+DB)
CCCC
CCCC     CALCULATE CENTERLINE ELEMENT IF NEEDED.
CCCC
      IF(JFIRST(I).GE.2) GO TO 200
```

Table 2: Continued

```
      DRSQ = DR(1)*DR(1)
      DENOM = 2.0*CONAB + DRSQ * (DA+DB)
      HOLD = 2.*CONAB*TEMP(I,2)+DRSQ*(DB*TEMP(I-1,1) +DA*TEMP(I+1,1))
      HOLD = HOLD / DENOM
      CALL RELAX(I,1,HOLD)
  200 CONTINUE
CCCC
CCCC     FINISH SWEEPING THE ROW.
CCCC
      JEND = LAST(I) -1
      JT = JFIRST(I)
CCCC
CCCC     CHECK IF CENTERLINE ELEMENT HAS BEEN CALCULATED.
CCCC
      IF (JT.EQ.1) JT = 2
      IF(JEND.LT.JT) GO TO 220
      DO 210 J=JT,JEND
      D1 = DR(J-1)
      D2 = DR(J)
      RAD = RDIST(J)
      TWORAD = 2. * RAD
      CONLR = D2 * D1* (D2 + D1)
      C1 = CONAB*(D1*D1 -D2*D2)
      C2 = TWORAD * CONAB * (D1+D2)
      C3 = TWORAD * CONLR * (DA+DB)
      HOLD = CONAB * D1 * (C1+TWORAD)*TEMP(I,J+1)
      HOLD = HOLD + CONAB*D2*(TWORAD-D2) * TEMP(I,J-1)
      HOLD = HOLD + TWORAD * CONLR *(DB*TEMP(I-1,J)+DA*TEMP(I+1,J))
      HOLD = HOLD /(C1+C2+C3)
      CALL RELAX(I,J,HOLD)
  210 CONTINUE
  220 CONTINUE
CCCC
CCCC     SWEEP COMPLETE.  CHECK FOR CONVERGENCE.
CCCC
      AVGDIF = DIFSUM / XNPTS
      DIFSUM = 0.0
      DIFER = DIFMAX
      DIFMAX = 0.
      IF ( DIFER.GT.DIFTOL) GO TO 260
      IF (AVGDIF.GT. AVGTOL) GO TO 260
CCCC
CCCC     COMPUTE THE TOTAL RATE OF HEAT FLOW (Q)
CCCC
      Q=0.0
      KR = 2
      DO 230 KQ=1,NCM1
      Q=Q + (RDIST(KQ+1)**2-RDIST(KQ)**2)*(TEMP(KR,KQ)+TEMP(KR,KQ+1) -
     *   TEMP(KR+1,KQ) -TEMP(KR+1,KQ+1))/2.0
  230 CONTINUE
      Q= 3.14159*XKMETL*Q/ 12.0 /DZ(KR)
      WRITE(6,240) Q
  240 FORMAT(//'1THE TOTAL HEAT FLOW RATE IS ', F16.5,'BTU/HR')
      CALL OUTPUT
      WRITE(6,250) N
  250 FORMAT(//'0THE NUMBER OF ITERATIONS WAS ',I4)
      GO TO 270
  260 CONTINUE
      CALL OUTPUT
  270 CONTINUE
```

Table 2: Continued

```
      STOP                                                              AR002280
      END                                                               AR002290
      SUBROUTINE RELAX(I,J,HOLD)
      COMMON      TEMP,RDIST,ZDIST,ABSDIF,DIFSUM,OMEGA,DIFMAX
      COMMON LAST,NROWS,NCOLS,JFIRST
      DIMENSION TEMP(20,20),LAST(20)   ,JFIRST(20)
      DIMENSION RDIST(20),ZDIST(20)
      DELAY = OMEGA * HOLD + (1.0 - OMEGA)*TEMP(I,J)
      ABSDIF = ABS(DELAY - TEMP(I,J))
      DIFSUM = DIFSUM+ ABSDIF
      IF (ABSDIF.GT.DIFMAX) DIFMAX = ABSDIF
      TEMP(I,J) = DELAY
      RETURN
      END
      SUBROUTINE OUTPUT
      COMMON      TEMP,RDIST,ZDIST,ABSDIF,DIFSUM,OMEGA,DIFMAX
      COMMON LAST, NROWS,NCOLS,JFIRST
      DIMENSION TEMP(20,20),LAST(20),JFIRST(20)
      DIMENSION TKEY(20)
      DIMENSION RDIST(20),ZDIST(20)
      NC= NCOLS
      IF(NC.GT.12) NC = 12
      WRITE (6,69) (RDIST(J),J=1,NC)
   69 FORMAT (////'0 DISTANCE    ',12F8.2//)
      DO 88 I=1,NROWS
      K=LAST(I)
      IF(K.GT.12) K=12
      WRITE(6,79) ZDIST(I),(TEMP(I,J),J=1,K)
   79 FORMAT(1H0  ,F8.4,5X,13F8.2)
   88 CONTINUE
      IF(NCOLS.LE.12) GO TO 100
      WRITE(6,89)
   89 FORMAT('1    THIS IS THE RIGHT HAND SIDE OF THE RESULTS.')
      WRITE(6,69) (RDIST(J),J=13,NCOLS)
      DO 99 I=1,NROWS
      K=LAST(I)
      WRITE(6,79) ZDIST(I),(TEMP(I,J),J=13,K)
   99 CONTINUE
  100 CONTINUE
      RETURN
      END
```

Table 2: Continued

```
    13    18     1      .4          33.        .1         .1
      THIS IS TEST DATA
280.        0.0        18
235.        .06        18
233.        .16        18
230.        .25        18
228.        .35        17
225.        .44        16
220.        .565       16
217.        .69        16
210.        .815       16
200.        .94        16
199.        1.065      16
180.        1.36       17
170.        1.70       18
430.        0.
420.        .1
410.        .2
400.        .3
390.        .4
380.        .5
370.        .6
350.        .7
340.        .8
325.        .9
310.        1.
300.        1.1
288.        1.25
285.        1.35
282.        1.4
281.        1.467
280.        1.55
280.        1.631
       6     1 240.
       6     2 238.
       6     3 237.
       6     4 237.
       6     5 236.
       6     6 236.
       6     7 235.
       6     8 234.
       6     9 233.
       6    10 233.
       6    11 233.
       6    12 230.
       6    13 229.
       7    13 228.
       8    13 225.
       9    13 215.
      10    13 200.
      11    13 150.
      12    13 165.
      13    13 175.
      20    20
```

Table 3

Sample Data Cards

THIS IS TEST DATA

DISTANCE	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.25	1.35	1.40	1.47	1.55	1.63
0.0000	430.00	420.00	410.00	400.00	390.00	380.00	370.00	350.00	340.00	325.00	310.00	300.00	288.00	285.00	282.00	281.00	280.00	280.00
0.0600	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	235.00
0.1600	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	233.00
0.2500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	233.00
0.3500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	228.00	
0.4400	240.00	238.00	237.00	237.00	236.00	236.00	235.00	234.00	233.00	233.00	233.00	230.00	229.00	0.00	0.00	225.00		
0.5650	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												228.00	0.00	0.00	220.00		
0.6900	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												225.00	0.00	0.00	217.00		
0.8150	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												215.00	0.00	0.00	210.00		
0.9400	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												200.00	0.00	0.00	200.00		
1.0650	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												190.00	0.00	0.00	190.00		
1.3600	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												185.00	0.00	0.00	0.00	180.00	
1.7000	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												175.00	0.00	0.00	0.00	0.00	170.00

THE TOTAL HEAT FLOW RATE IS 366.70360BTU/HR

DISTANCE	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.25	1.35	1.40	1.47	1.55	1.63
0.0000	430.00	420.00	410.00	400.00	390.00	380.00	370.00	350.00	340.00	325.00	310.00	300.00	288.00	285.00	282.00	281.00	280.00	280.00
0.0600	248.36	248.00	247.37	246.54	245.54	244.41	243.12	241.59	240.09	238.55	236.96	235.48	233.62	232.82	232.55	232.47	232.83	235.00
0.1600	244.73	244.56	244.19	243.45	242.63	241.68	240.57	239.32	238.08	236.80	235.49	234.18	232.52	231.76	231.55	231.49	231.85	233.00
0.2500	242.19	241.99	241.58	241.04	240.33	239.53	238.56	237.49	236.43	235.39	234.27	232.57	231.36	230.47	230.17	229.57	230.01	233.00
0.3500	240.14	239.65	239.12	238.71	238.03	237.46	236.58	235.61	234.69	234.02	233.19	231.56	229.99	228.71	228.22	227.83	228.00	
0.4400	240.00	238.00	237.00	237.00	236.00	236.00	235.00	234.00	233.00	233.00	233.00	230.00	229.00	226.86	225.56	225.00		
0.5650	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												228.00	223.85	222.14	220.00		
0.6900	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												225.00	215.71	218.14	217.00		
0.8150	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												215.00	211.56	210.59	[illegible]		
0.9400	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												200.00	200.55	200.40	200.00		
1.0550	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												190.00	191.29	191.09	190.00		
1.3500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												185.00	183.38	182.58	181.46	180.00	
1.7000	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU												175.00	173.43	175.14	174.27	172.49	170.00

Table No. 4: Program Output

to surface temperatures, certain interior temperatures are needed to develop the mathematical model. For these reasons, a program was undertaken to establish operational temperatures for a ceramic coated piston and exhaust valve. Needed information included temperature data at known points for various power levels for uncoated parts and for parts with 0.040 inch, 0.070 inch and 0.100 inch coating of plasma sprayed yttrium stabilized zirconium oxide.

TEST FACILITIES

The engine selected for acquisition of temperature data was the same as that used for the previous performance data of ceramic coated parts. This was a cooperative fuel research (CFR) engine incorporating the low speed crankcase and the split cylinder head. The engine and the associated laboratory are shown in figure 12. An engine schematic is illustrated in figure 13.

Intake air was drawn through an ice tower to control humidity. It then passed through a flow control system consisting of a laminar flow element, a surge chamber and a throttle valve. By this method a constant humidity, pressure and temperature of air was available to the engine for all tests.

Fuel for all tests was commercial liquified petroleum gas (LPG).

Lubricating oil temperature was controllable by an electric heater located in the oil sump. Engine cooling was by the standard CFR boiling water jacket.

Engine power output was measured by an indicated mean effective pressure (IMEP) method. This technique incorporates a strain gauge pressure transducer located in the combustion chamber, an engine rotational position transducer on the crankshaft and a cycle indicator located on the camshaft. These three transducers provide the necessary data input to a PET 2001-8 computer for the solution of the following equation:

$$IMEP = \oint pdv \qquad (20)$$

The average of several of the above solutions provides an average

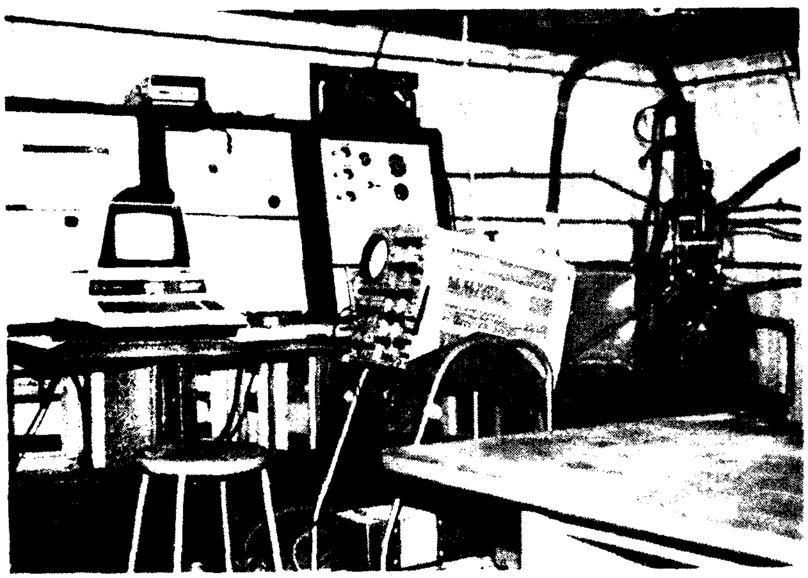

Figure 12: Engine Laboratory

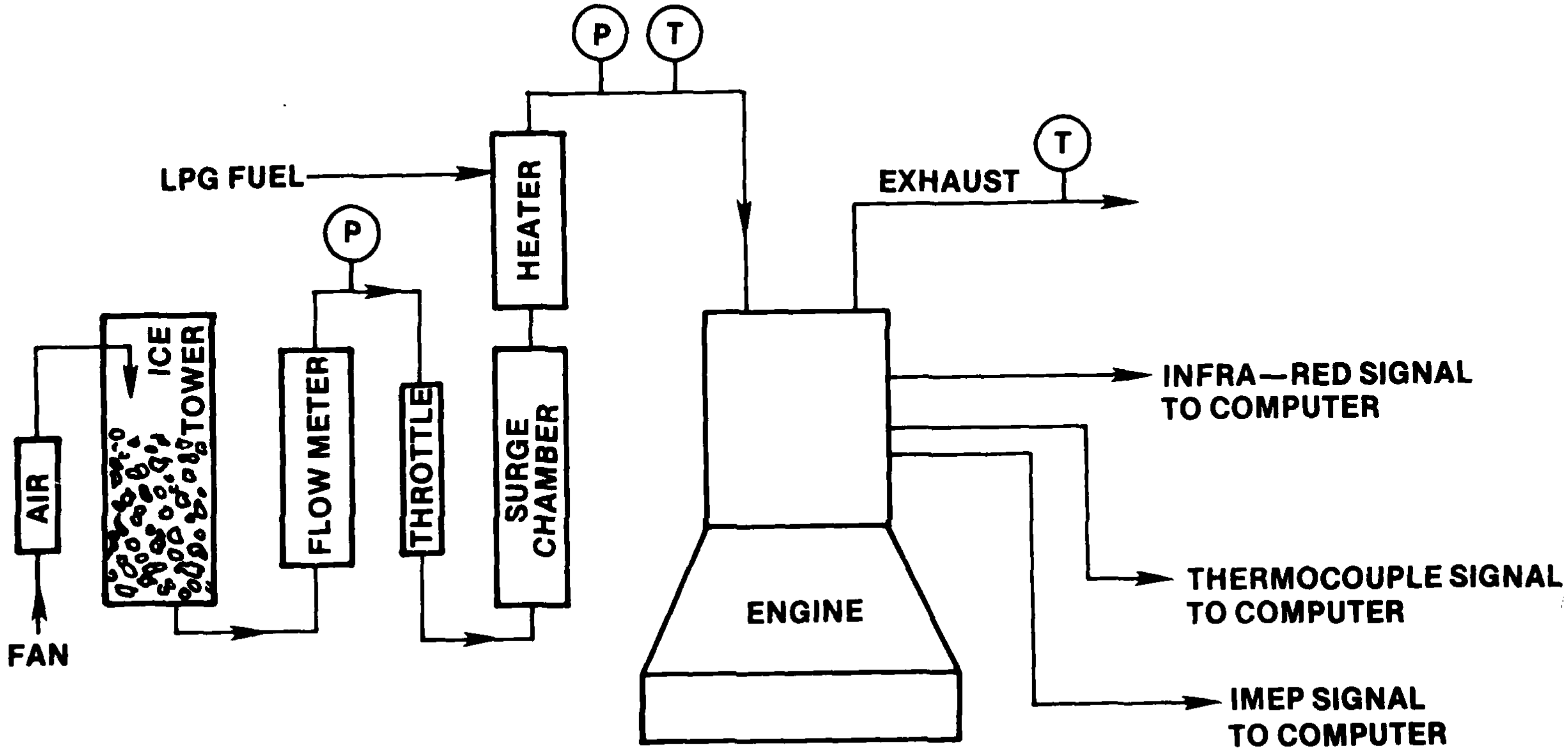

Figure 13: Engine Schematic

value of the IMEP for any operational condition. This value is recorded as engine power level.

Those familiar with temperature measurement recognize the problems in establishing accurate data at point sources in ceramic substances. Such sources on the interior of metallic parts also offer a significant challenge. Finally, when one locates these points on a reciprocating piston (valve) of an operational engine, the full complexity of the situation becomes apparent.

The above problem can be subdivided into two parts: 1) what method should be used to measure each point temperature, and 2) how should the signal be transmitted from moving parts to the exterior of the engine?

Historically, thermocouples (including thin film deposited types), deposited thin film resistors, thermisters and Templugs have been successfully used for general temperature measurement.

Plasma sprayed surfaces are relatively porous which would greatly reduce the probability of successful application of thin film deposited type devices. Ceramic surfaces that are attached to a metal structure make the attachment and routing of leadwires nearly impossible.

In this project, the ceramic surface must be reduced from 0.100 inch thickness to zero in three stages by a surface grinding technique. Such a process would necessarily destroy any surface device and require the reinstallation and recalibration of a new one.

Templugs are a threaded metal insert that measure temperature by hardness change. These devices measure only the peak temperature and would not be compatible with a plasma sprayed surface.

Recognizing the problems with temperature measurement on a ceramic surface in the combustion chamber of a reciprocating I-C engine, it was decided that optical techniques offered the best hope of success.

It is known that all surfaces emit an infrared radiation as a direct function of surface temperature. Therefore, if this signal could be viewed and transmitted outside the engine, a method would have been found to instantaneously measure surface temperature without touching or affecting the surface.

The infrared signal transmission problem was solved by a system of water cooled probes that incorporated a glass fiber optics bundle. One bundle was designed so it could view both the top and surface of the piston and the lower surface of the exhaust valve. Both of these surfaces were within the chamber. A second bundle was used to view the exhaust valve tulip (manifold) surface. Details of these probes and associated hardware follows.

Figure 14 shows details of an actual fiber optics bundle and the water cooled probe into which it is assembled. This probe is shown in position on the engine in figure 15. Note that the probe fits into a deck spacer between the engine cylinder and cylinder head. This technique allows the probe to be moved in and out to view various radial positions and to be rotated 180° to alternately inspect the piston and the valve surface.

Figure 16 displays details of a second water cooled probe designed to view the exhaust valve tulip. Installation of this probe into the CFR cylinder head is seen in figure 17.

The optical signal from both of these probes is transmitted by flexible fiber optics to a detector that converts the I-R signal to an electric voltage. The electric signal is read as a temperature by an analyzer.

During the tests the PET 2001-8 computer seved as the I-R temperature readout device, reading each probe temperature at a selected engine position. For the piston, the reading position was the top dead center (TDC) position on the exhaust-intake overlap event. The combustion chamber valve surface was read at this same cyclic position. The valve tulip was monitored with the valve closed at the BDC position at the end of the intake stroke.

SEMIADIABATIC PISTON

As stated previously, piston temperatures were required both on the combustion chamber and crankcase surfaces, as well as on selected points on the interior of the metallic structure. Instrumentation plans called for the piston combustion chamber surface to be measured

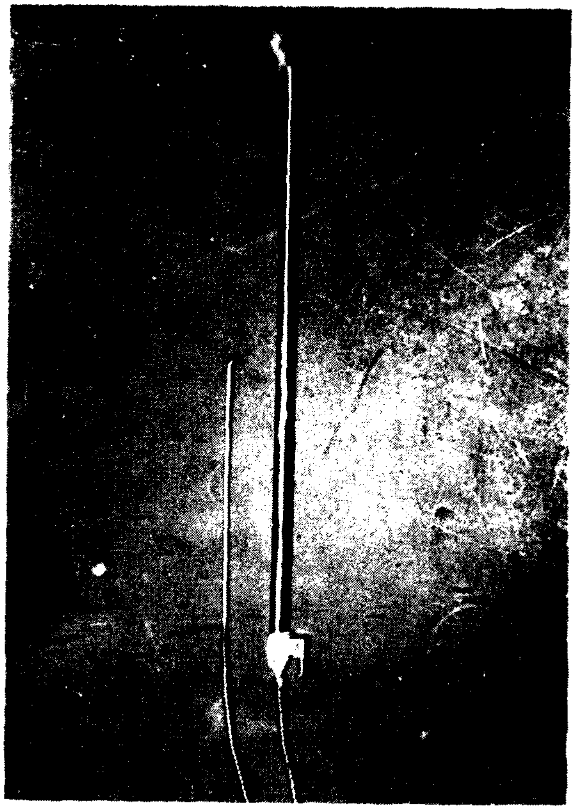

Figure 14: Fiber Optics
Combustion Chamber

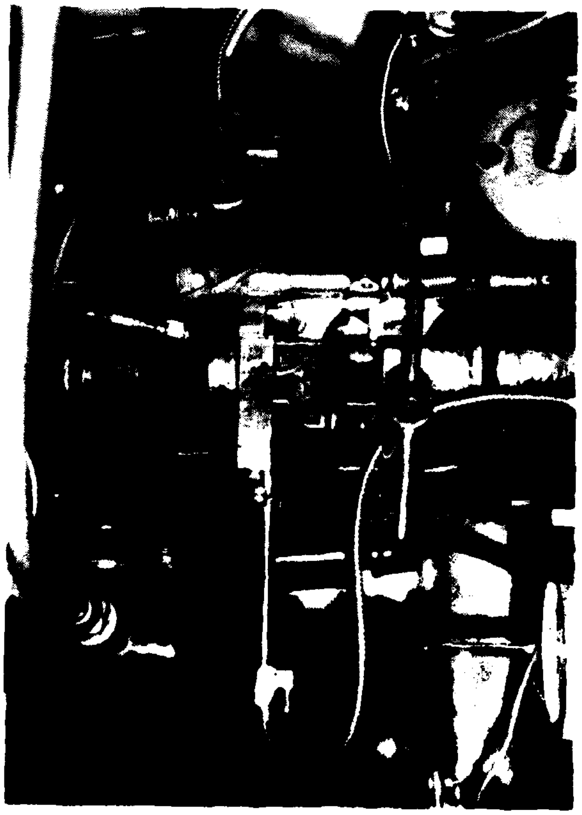

Figure 15: Combustion Chamber
Probe Installation

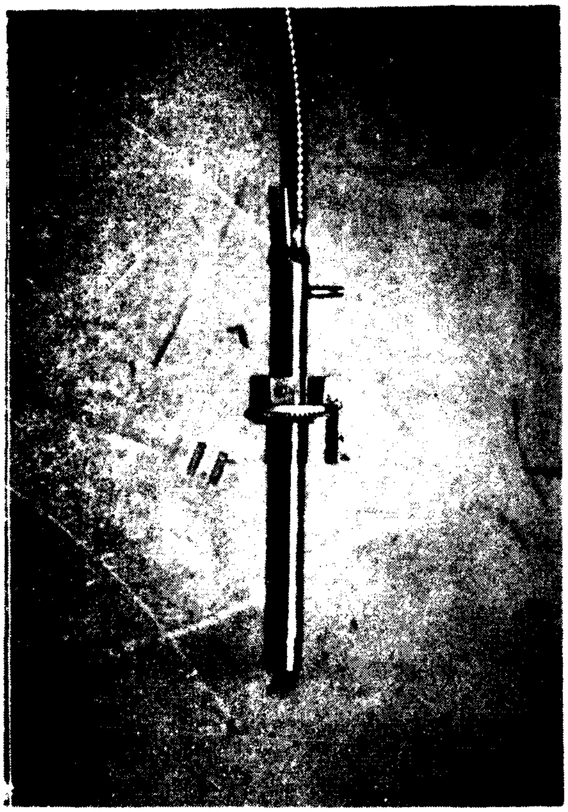

Figure 16: Fiber Optics Exhaust Port

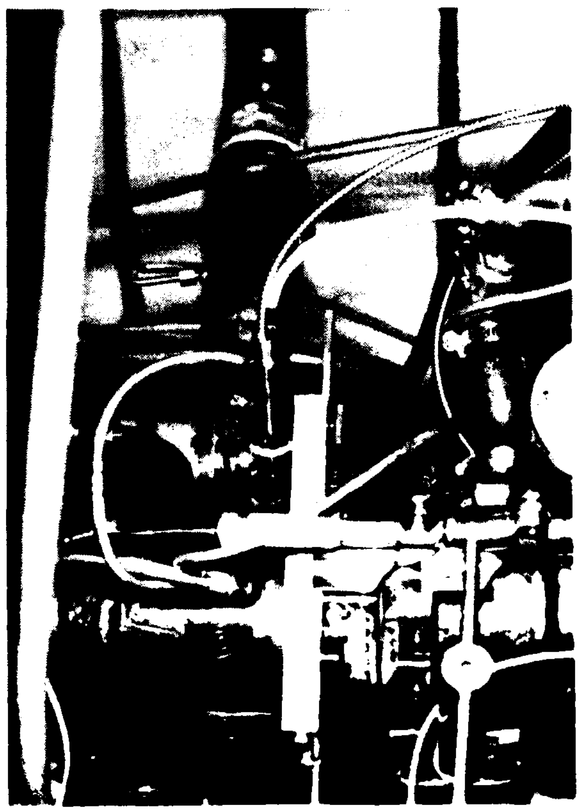

Figure 17: Exhaust Port
Probe Installation

by an infrared probe while all other temperatures used thermocouples.

The basic piston design adopted is seen in cross section in figure 18 and in assembly in figure 19. This is a three component piston consisting of a steel crown, a phenolic spacer and an aluminum skirt in assembly. The crown is fastened to the skirt by a series of screws.

The piston crown is a symmetrical design (to insure two direction heat flow) with access holes drilled for interior thermocouple insertion. These thermocouples were held in place by a ceramic cement. Other thermocouples are attached to the lower surface by peening. Figure 20 identifies the position of the eleven thermocouples used. Figure 21 shows the piston crown with thermocouples installed. Also shown, in position, is the phenolic insulator. Note that a series of holes have been designed into each side of the insulator. These holes provide a screw type connection between the fine wire (0.015 inch) iron constantan thermocouples and the stranded 30 gauge leadwire. Thirteen wires are routed through the piston skirt shown in figure 22 and 23; two of these wires served as redundant commons while the other eleven were signal wires for each of the eleven thermocouples.

THERMOCOUPLE WIRE ROUTING

Leadwire termination on the piston was by high temperature epoxy, as was the attachment to the connecting rod. Note in figure 24 that stress relief loops have been placed at the junction between the piston and connecting rod.

At the big end of the connecting rod another stress relief loop joined the span between the connecting rod and the swivel of a multibar support mechanism. This mechanism was designed to penetrate the crankcase at a sliding-rotating bearing and provide support for the thermocouple leadwires. An exterior view of this device is seen in figure 25. The base of the multibar mechanism is a pin joint attached to the engine baseplate. The thermocouple wires continue from this location through a selector switch to computer and digital readout.

The exhaust valve configuration without ceramic coating is shown

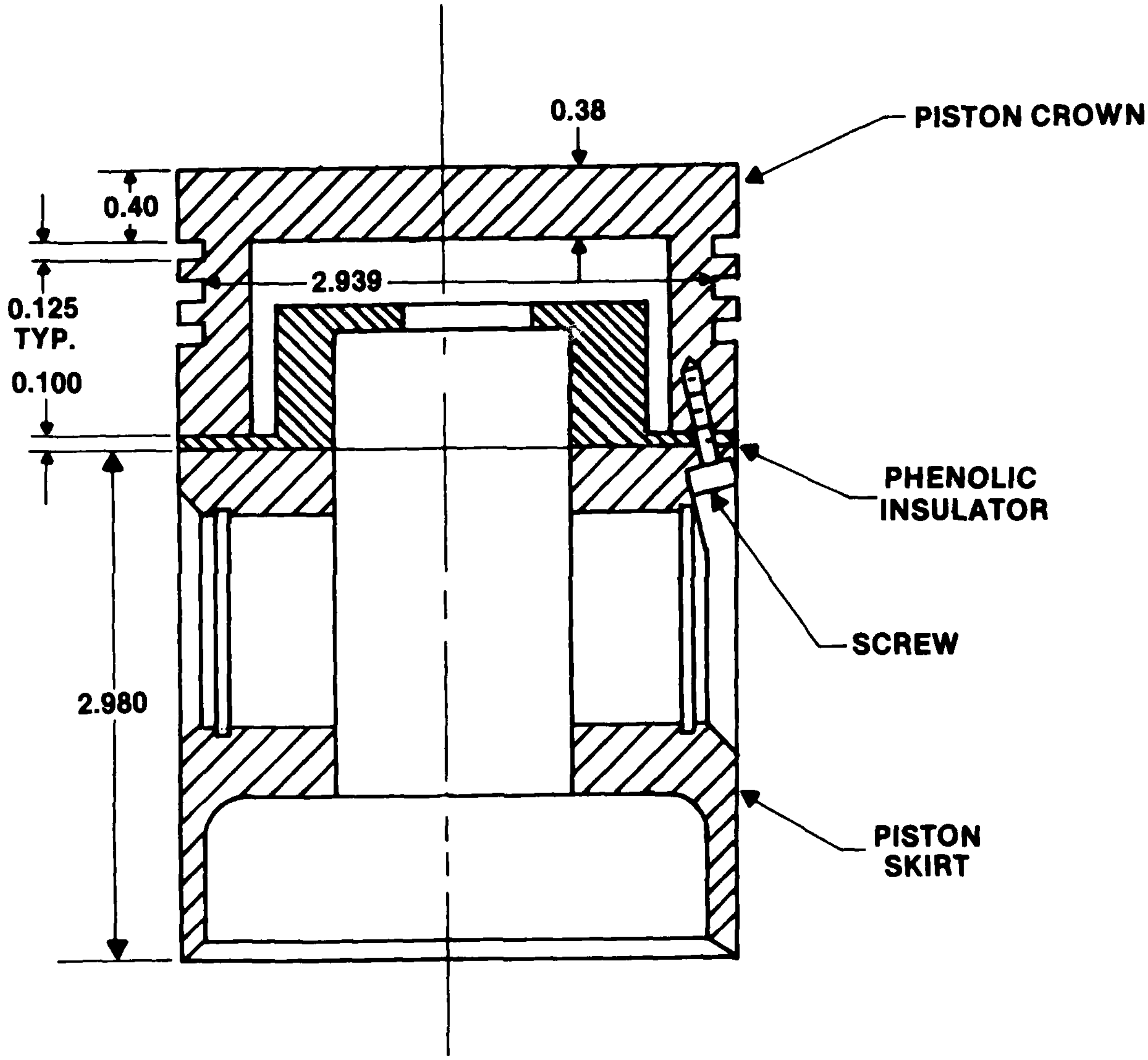

Figure 18: Piston Cross Section

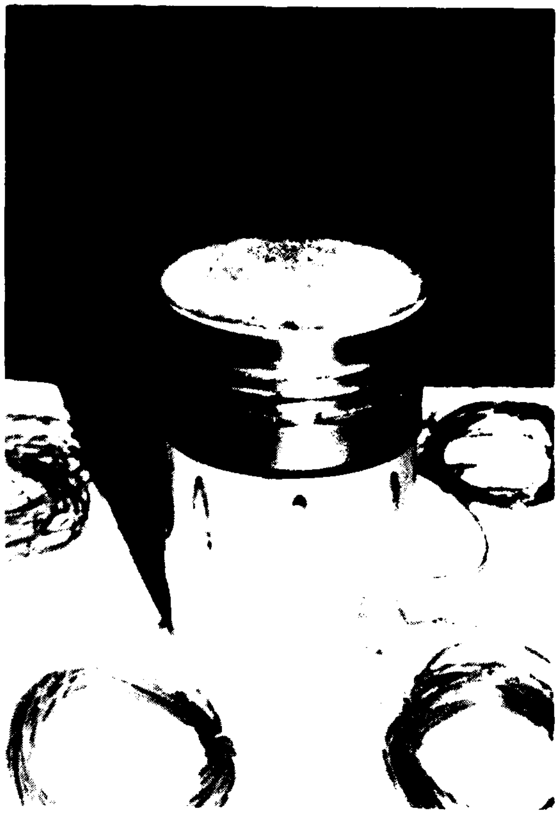

Figure 19: Piston Assembly

Thermocouple Number	R Inches	Z Inches
1	0	0.110
2	0.375	0.110
3	0.805	0.110
4	1.188	0.110
5	0.109	0.470
6	0.375	0.470
7	0.750	0.470
8	1.031	0.470
9	1.607	0.110
10	1.607	0.916
11	1.607	1.150

Note: The Dimension Z is measured from the top surface of the ceramic. Values shown are for 0.100 thickness of coating.

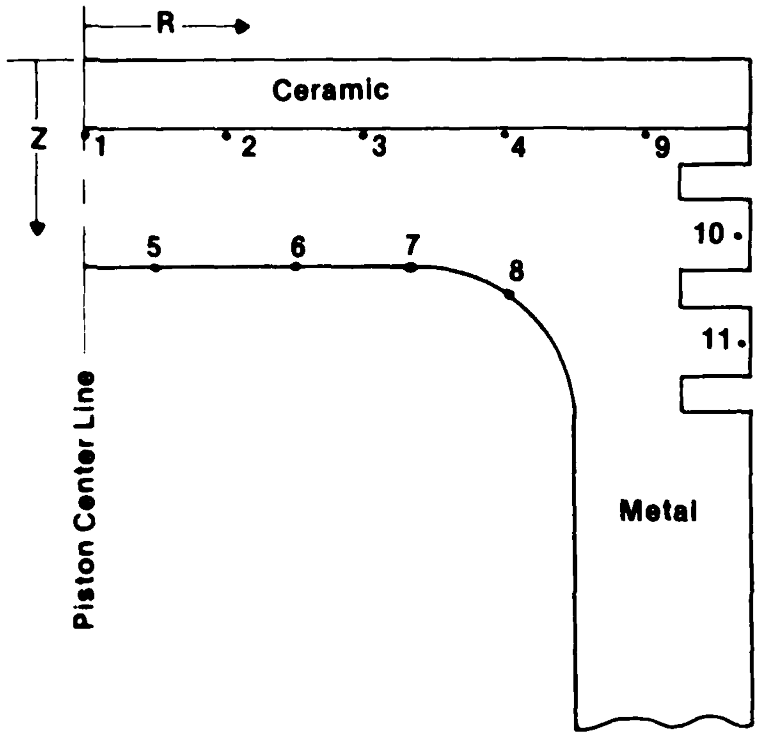

Figure [illegible]: Thermocouple Position

Figure 21: Thermocouple Installation

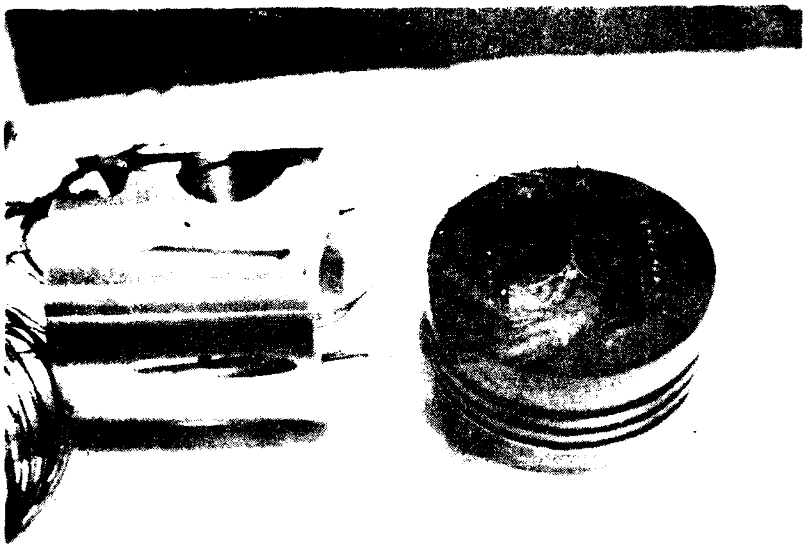

Figure 22: Piston Leadwire Installation

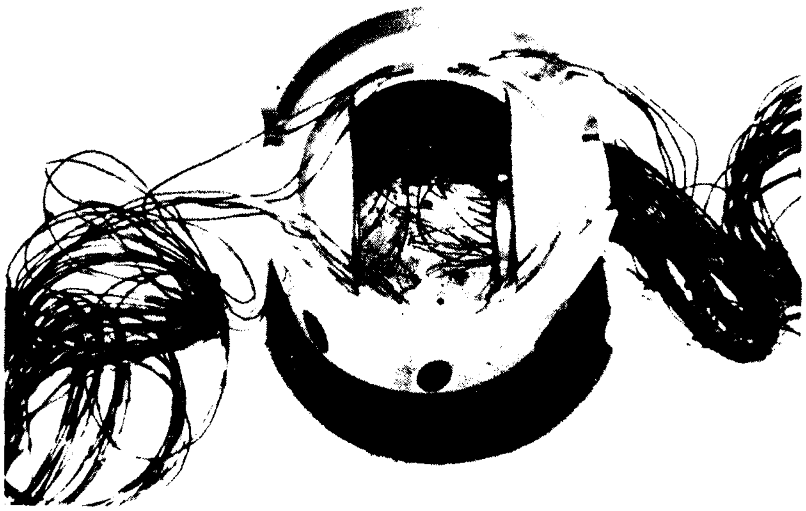

Figure 23: Piston Leadwire Routing

Figure 24: Piston-Connecting Rod Assembly

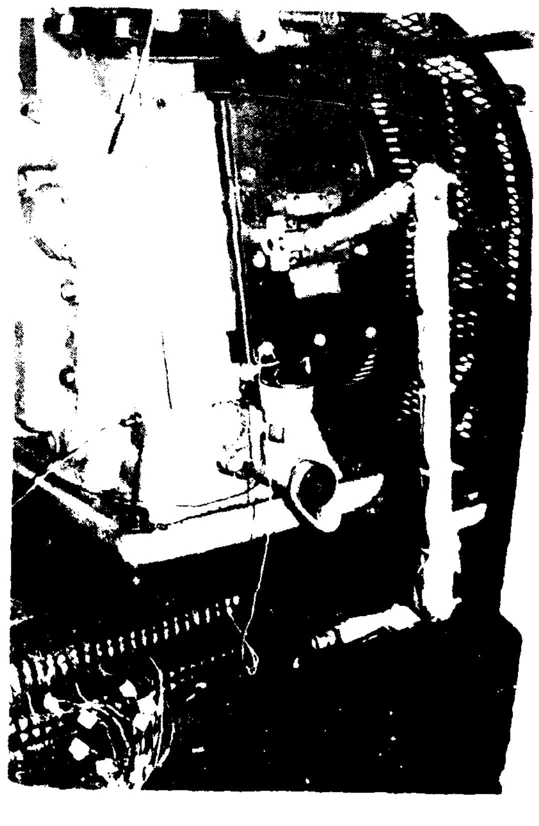

Figure 25: Multilink Support Mechanism

in figure 26. As with the piston a 0.100 inch coating of yttrium stabilized zirconium oxide was applied by plasma spray. Coating thickness was reduced to 0.070, 0.040 and 0.000 inches for repeated tests. Controlled valve seat contact was established by hand grinding, lapping and fitting. Special gauges were fabricated to insure repeatability of valve seat contact. The valve grid network utilized in this test is defined by radial locations as viewed by the fiber optics probe and as portrayed in figure 27.

ENGINE ASSEMBLY

Figure 28 portrays the engine as assembled for final test. Noteworthy items are:

(A) Engine rotational position transducers

(B) Cycle position transducer

(C) Multibar support mechanism

(D) Deck spacer with fiber optics.

Engine test specifications follow in table 5:

Table 5

Bore	3.25 inch
Stroke	4.50 inch
Compression ratio	6.5 to 1
Cooling water temperature	210° F
Lubricating oil temperature	120° F
Ignition timing	10° BTDC
RPM	630
Fuel	Commercial liquified Petroleum gas

TEST PROCEDURE AND DATA

The data required for ceramic coating evaluation was as follows:

1) Metal ceramic interface temperature or thermocouple output for numbers 1, 2, 3, 4, & 9.

2) Ring belt temperature or thermocouple output for number 10 & 11.

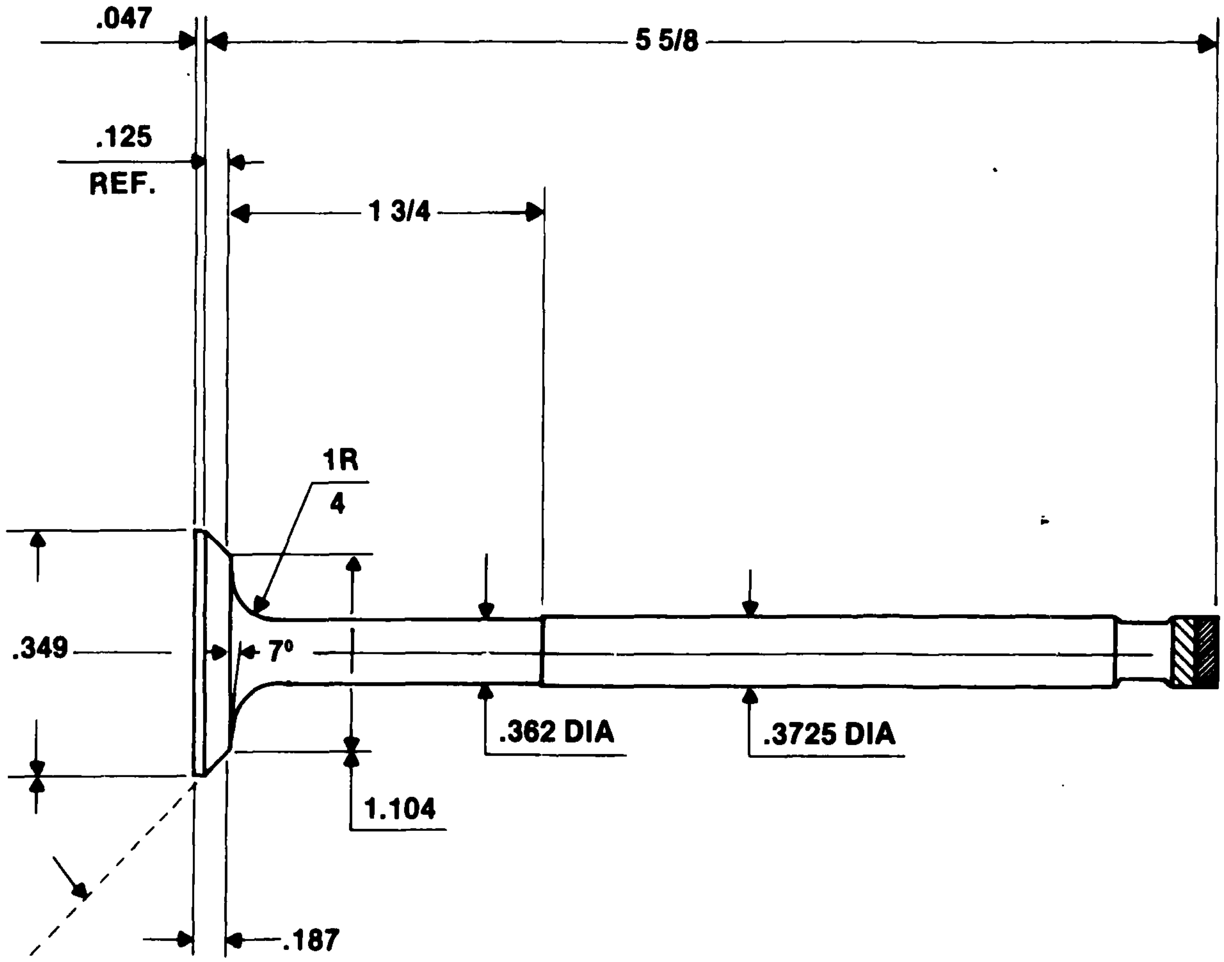

Figure 26: Valve Configuration

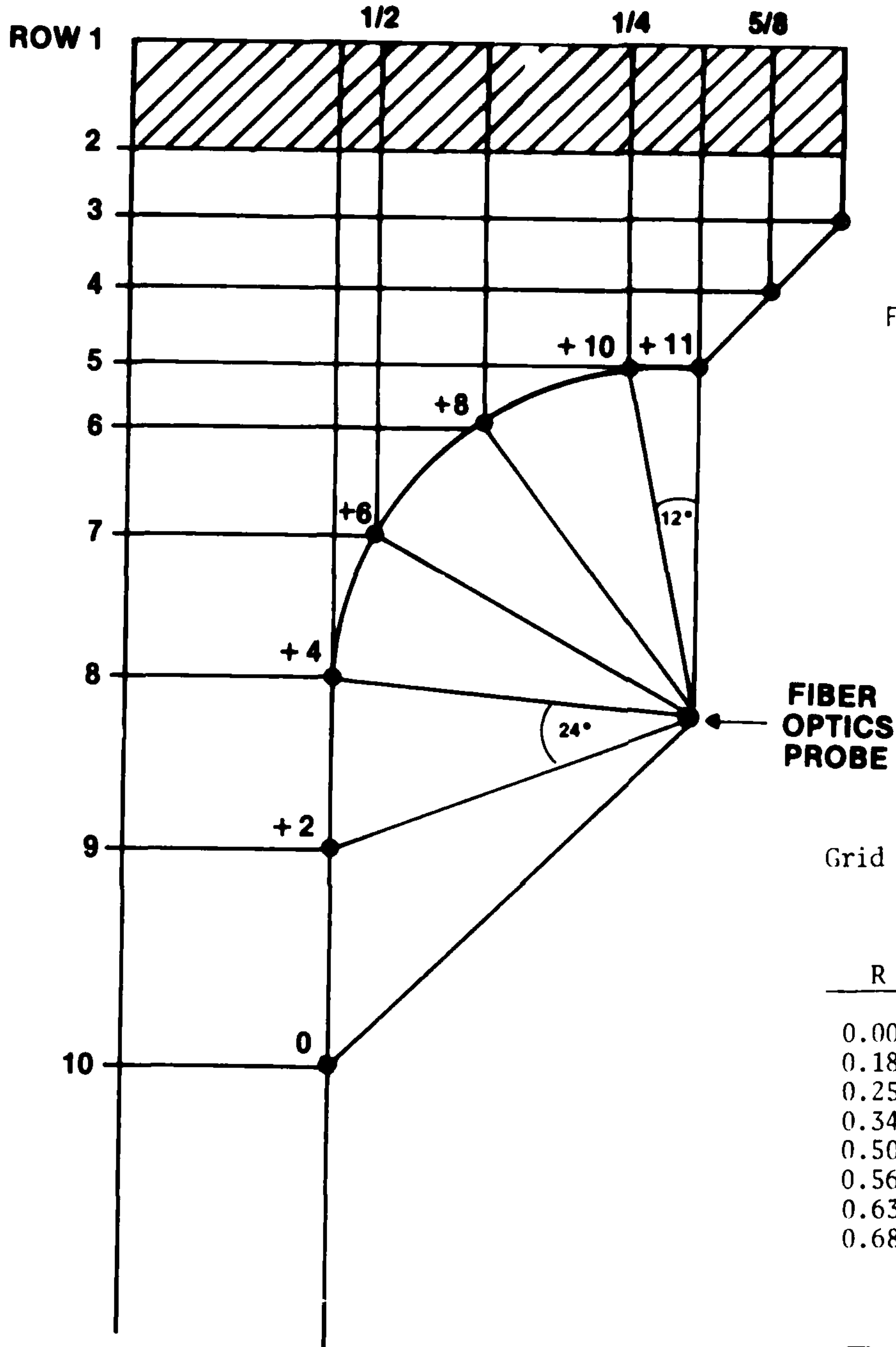

Figure 27: Valve Grid Network

Grid Point Distance

Inches

R	Z
0.00	0.00
0.18	CT
0.25	CT + 0.05
0.34	CT + 0.13
0.50	CT + 0.20
0.56	CT + 0.27
0.63	CT + 0.37
0.68	CT + 0.51
	CT + 0.68
	CT + 0.88

CT = Coating Thickness

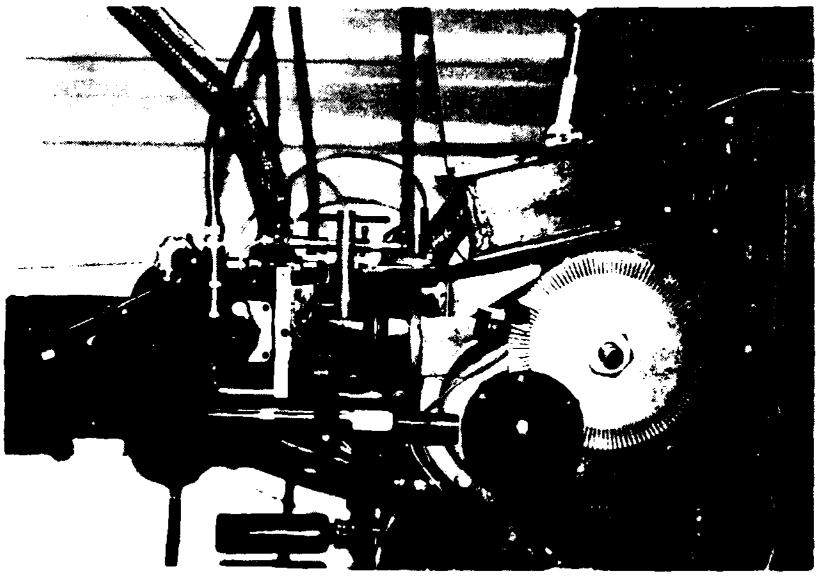

Figure 28: Engine Assembly

3) Crankcase surface temperature or thermocouple output for numbers 5, 6, 7, & 8.

4) Piston and valve combustion chamber surface or infrared output at various radial positions.

5) Valve tulip surface temperature at various positions.

The above data values were determined for ceramic coating thickness of 0.100, 0.070, 0.040, 0.000 inches at 5 power levels corresponding to 100%, 75%, 50%, 25% and motoring. This data is displayed in the top profiles of tables 6 & 7, respectively. Interpretation of tabulation has previously been outlined. Heat transfer and the calculated temperature and distribution is shown below the top profile. Maximum power for this version of the CFR engine corresponded to an indicated mean effective pressure of 40.5 psi. In each test, a fuel flow was established that produced this rated power. Fuel flow was incrementally reduced to produce the indicated steps of reduced power. Engine temperatures were allowed to stabilize before data was taken.

DATA ANALYSIS

The results of the preceding calculations are displayed in tables 8 and 9. Table 8 displays heat transfer information based on boundary conditions using infrared data as well as thermocouples. Table 9 is comparative data for the piston only, based on thermocouple data.

In both cases, the data shows the expected reduction in heat flow with increased coating thickness. The correlation between the sets of data, however, is not good. The great difference in heat flow for infrared and noninfrared calculations leads one to believe that the accuracy of the surface temperature measurement is poor.

ENDURANCE TEST

As previously stated, a part of this project was to establish the endurance behavior for zirconium oxide coated engine parts. Actually, the test described, herein, was the continuation of a 1000 hour en-

CERAMIC = 100/1000, POWER= 100 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	598.00	603.00	604.00	592.00	575.00	544.00	513.00	513.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	532.00
0.1500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	540.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	532.00	
0.3000	0.00	0.00	0.00	0.00	548.00			
0.3700	0.00	0.00	0.00	558.00				
0.4700	0.00	0.00	563.00					
0.6100	0.00	549.00						
0.7800	0.00	545.00						
0.9800	0.00	527.00						

THE TOTAL HEAT FLOW RATE IS -35.21391BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	598.00	603.00	604.00	592.00	575.00	544.00	513.00	513.00
0.1000	555.71	554.98	553.89	551.48	544.16	540.68	538.11	532.00
0.1500	555.48	554.70	553.59	551.23	543.98	540.66	538.26	540.00
0.2300	555.60	555.10	554.22	552.15	544.70	539.53	532.00	
0.3000	556.04	556.14	555.81	554.42	548.00			
0.3700	556.43	557.47	558.24	558.00				
0.4700	555.90	555.58	563.00					
0.6100	549.59	549.00						
0.7800	543.85	545.00						
0.9800	531.86	527.00						

Table 6

Valve Temperature Profiles

CERAMIC = 100/1000, POWER= 75 PER CENT

DISTANCE	0.00	0.19	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	522.00	923.00	481.00	517.00	572.00	579.00	585.00	585.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	496.00
0.1500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	506.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	496.00	
0.3000	0.00	0.00	0.00	0.00	514.00			
0.3700	0.00	0.00	0.00	522.00				
0.4700	0.00	0.00	505.00					
0.6100	0.00	504.00						
0.7800	0.00	505.00						
0.9800	0.00	476.00						

THE TOTAL HEAT FLOW RATE IS -26.52177BTU/HR

DISTANCE	0.00	0.19	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	522.00	923.00	481.00	517.00	572.00	579.00	585.00	585.00
0.1000	515.52	515.52	515.30	514.21	509.35	506.35	504.29	496.00
0.1500	515.91	517.49	515.52	514.19	508.97	505.91	503.80	506.00
0.2300	514.86	515.65	515.45	515.24	509.70	504.07	496.00	
0.3000	513.45	514.37	515.42	517.72	514.00			
0.3700	511.49	512.36	514.35	522.00				
0.4700	507.78	506.87	505.00					
0.6100	504.46	504.00						
0.7800	501.93	505.00						
0.9800	484.89	476.00						

Table 6 (continued)

Valve Temperature Profiles

CERAMIC = 100/1000, POWER= 50 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	477.00	477.00	477.00	477.00	476.00	477.00	478.00	478.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	512.00
0.1500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	522.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	512.00	
0.3000	0.00	0.00	0.00	0.00	532.00			
0.3700	0.00	0.00	0.00	542.00				
0.4700	0.00	0.00	543.00					
0.6100	0.00	526.00						
0.7800	0.00	532.00						
0.9800	0.00	500.00						

THE TOTAL HEAT FLOW RATE IS -78.49364BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	477.00	477.00	477.00	477.00	476.00	477.00	478.00	478.00
0.1000	534.54	534.19	533.45	531.63	524.67	521.23	519.14	512.00
0.1500	534.91	534.65	533.80	531.96	524.96	521.50	519.39	522.00
0.2300	535.73	535.73	535.31	533.90	526.65	520.26	512.00	
0.3000	536.46	537.13	537.46	537.26	532.00			
0.3700	536.70	538.37	540.01	542.00				
0.4700	535.61	536.25	543.00					
0.6100	528.47	526.00						
0.7800	527.83	532.00						
0.9800	508.02	500.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 100/1000, POWER= 25 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	476.00	476.00	476.00	476.00	475.00	475.00	475.00	475.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	596.00
0.1500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	606.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	596.00	
0.3000	0.00	0.00	0.00	0.00	602.00			
0.3700	0.00	0.00	0.00	598.00				
0.4700	0.00	0.00	590.00					
0.6100	0.00	594.00						
0.7800	0.00	573.00						
0.9800	0.00	576.00						

THE TOTAL HEAT FLOW RATE IS -110.51210BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	476.00	476.00	476.00	476.00	475.00	475.00	475.00	475.00
0.1000	592.68	593.59	594.42	595.77	598.31	595.15	600.67	595.00
0.1500	593.42	594.31	595.14	596.50	599.06	599.91	601.43	606.00
0.2300	594.00	594.91	595.81	597.40	600.15	600.16	596.00	
0.3000	593.95	594.78	595.77	597.91	602.00			
0.3700	593.39	593.97	594.77	598.00				
0.4700	591.99	591.83	590.00					
0.6100	590.35	594.00						
0.7800	576.49	573.00						
0.9800	576.14	576.00						

Table 6 (continued)

Valve Temperature Profiles

CERAMIC = 100/1000, POWER = 00 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	497.00	566.00	589.00	569.00	540.00	527.00	515.00	515.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	674.00
0.1500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	684.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	674.00	
0.3000	0.00	0.00	0.00	0.00	685.00			
0.3700	0.00	0.00	0.00	686.00				
0.4700	0.00	0.00	694.00					
0.6100	0.00	685.00						
0.7800	0.00	675.00						
0.9800	0.00	652.00						

THE TOTAL HEAT FLOW RATE IS -116.41070BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	497.00	566.00	589.00	569.00	540.00	527.00	515.00	515.00
0.1000	681.67	682.42	682.34	681.47	679.49	678.62	676.87	674.00
0.1500	682.82	683.14	682.91	682.16	680.33	679.54	675.86	684.00
0.2300	684.44	684.56	684.27	683.52	681.90	679.55	674.00	
0.3300	685.80	686.08	685.86	684.53	685.00			
0.3700	686.99	687.84	688.01	686.00				
0.4700	687.81	690.37	694.00					
0.6100	693.61	685.00						
0.7800	674.04	675.00						
0.9800	658.35	652.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 70/1000, POWER = 100 PER CENT

DISTANCE	0.00	0.13	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	532.00	550.00	556.00	546.00	532.00	532.00	533.00	533.00
0.0700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	537.00
0.1200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	547.00
0.2000	0.00	0.00	0.00	0.00	0.00	0.00	537.00	
0.2700	0.00	0.00	0.00	0.00	548.00			
0.3400	0.00	0.00	0.00	550.00				
0.4400	0.00	0.00	548.00					
0.5800	0.00	545.00						
0.7500	0.00	535.00						
0.9500	0.00	532.00						

THE TOTAL HEAT FLOW RATE IS -60.89110BTU/HR

DISTANCE	0.00	0.19	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	532.00	550.00	556.00	546.00	532.00	532.00	533.00	533.00
0.0700	547.50	547.83	547.80	547.23	544.94	543.93	543.55	537.00
0.1200	547.65	547.84	547.74	547.25	545.05	543.93	543.64	547.00
0.2000	547.70	547.96	547.97	547.75	545.65	543.03	537.00	
0.2700	547.78	546.11	548.36	546.72	548.00			
0.3400	547.58	548.09	548.55	550.00				
0.4400	546.76	547.39	548.00					
0.5800	544.33	545.00						
0.7500	539.20	535.00						
0.9500	534.08	532.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 70/1000, POWER= 75 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	580.00	571.00	568.00	567.00	565.00	564.00	564.00	564.00
0.0700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	716.00
0.1200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	726.00
0.2000	0.00	0.00	0.00	0.00	0.00	0.00	716.00	
0.2700	0.00	0.00	0.00	0.00	726.00			
0.3400	0.00	0.00	0.00	727.00				
0.4400	0.00	0.00	726.00					
0.5800	0.00	716.00						
0.7500	0.00	650.00						
0.9500	0.00	685.00						

THE TOTAL HEAT FLOW RATE IS -153.06910BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	580.00	571.00	558.00	567.00	565.00	564.00	564.00	564.00
0.0700	717.88	718.32	718.63	719.02	719.02	718.94	719.98	716.00
0.1200	719.10	719.61	719.95	720.34	720.35	720.28	721.33	726.00
0.2000	720.70	721.46	721.97	722.58	722.56	720.92	716.00	
0.2700	721.64	722.77	723.62	724.77	726.00			
0.3400	721.88	723.57	724.90	727.00				
0.4400	720.47	723.16	726.00					
0.5800	712.90	716.00						
0.7500	693.62	650.00						
0.9500	687.48	685.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 70/1000, POWER= 50 PER CENT

DISTANCE	0.00	[illegible]	0.25	0.34	0.50	0.56	0.63	0.69
0.0000	542.00	53[illegible]	[illegible]28.00	528.00	528.00	531.00	344.00	534.00
0.0700	0.00	[illegible]	0.00	0.00	0.00	0.00	0.00	650.00
0.1200	0.00	[illegible]	0.00	0.00	0.00	0.00	0.00	660.00
0.2000	0.00	[illegible]	0.00	0.00	0.00	0.00	650.00	
0.2700	0.00	[illegible]	0.00	0.00	666.00			
0.3400	0.00	0.00	0.00	673.00				
0.4400	0.00	0.00	667.00					
0.5300	0.00	655.00						
0.7500	0.00	653.00						
0.9500	0.00	653.00						

THE TOTAL HEAT FLOW RATE IS -157.64140BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.69
0.0000	542.00	532.00	528.00	528.00	528.00	531.00	344.00	534.00
0.0700	661.43	661.46	661.37	660.65	657.17	655.22	652.79	650.00
0.1200	662.48	662.61	662.54	662.01	658.29	656.30	655.46	660.00
0.2000	664.11	664.53	664.78	664.77	660.36	656.5[illegible]	650.00	
0.2700	665.24	666.[illegible]7	666.93	668.33	656.00			
0.3400	665.90	667.05	668.60	673.00				
[illegible]	665.60	666.[illegible]3	667.00					
0.5300	663.29	655.00						
0.7500	654.87	653.00						
0.9500	653.54	653.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 70/1000, [illegible] = 25 PER CENT

DISTANCE	0.00	[illegible]	0.25	0.34	0.51	0.56	0.63	0.68
0.0000	569.00	571.00	572.00	575.00	579.00	573.00	567.00	567.00
0.0700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	685.00
0.1200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	695.00
0.2000	0.00	0.00	0.00	0.00	0.00	0.00	685.00	
0.2700	0.00	0.00	0.00	0.00	701.00			
0.3400	0.00	0.00	0.00	708.00				
0.4400	0.00	0.00	709.00					
0.5800	0.00	710.00						
0.7500	0.00	700.00						
0.9500	0.00	683.00						

THE TOTAL HEAT FLOW RATE IS -132.87420BTU/HR

DISTANCE	0.00	0.13	0.25	0.34	0.51	0.56	0.63	0.68
0.0000	569.00	571.00	572.00	575.00	579.00	573.00	567.00	567.00
0.0700	698.75	695.53	698.19	697.06	692.94	659.88	690.20	685.00
0.1200	699.89	699.65	699.20	698.12	693.93	691.90	691.26	695.00
0.2000	701.88	701.78	701.50	700.67	696.19	691.76	685.00	
0.2700	703.69	703.89	703.98	703.54	701.00			
0.3400	705.38	705.97	706.55	708.00				
0.4400	707.18	708.26	709.00					
0.5800	707.45	710.00						
0.7500	695.48	700.00						
0.9500	687.75	683.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 70/100, POWER= 00 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	520.00	516.00	517.00	516.00	515.00	515.00	515.00	515.00
0.0700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	678.00
0.1200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	688.00
0.2000	0.00	0.00	0.00	0.00	0.00	0.00	678.00	
0.2700	0.00	0.00	0.00	0.00	687.00			
0.3400	0.00	0.00	0.00	685.00				
0.4400	0.00	0.00	675.00					
0.5800	0.00	665.00						
0.7500	0.00	667.00						
0.9500	0.00	673.00						

THE TOTAL HEAT FLOW RATE IS -159.82300BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	520.00	513.00	517.00	516.00	515.00	515.00	515.00	515.00
0.0700	673.68	674.94	676.01	677.55	679.59	680.10	681.61	678.00
0.1200	675.03	676.33	677.40	678.96	681.01	681.53	682.06	688.00
0.2000	676.37	677.34	679.15	681.15	683.40	682.44	678.00	
0.2700	676.59	678.25	680.01	683.10	687.00			
0.3400	675.81	677.50	679.73	685.00				
0.4400	672.90	673.69	675.00					
0.5800	667.26	665.00						
0.7500	667.70	667.00						
0.9500	671.48	673.00						

Table 6 (continued)
Valve Temperture Profiles

CERAMIC = 40/1000, POWER= 100 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	588.00	555.00	544.00	550.00	560.00	536.00	511.00	511.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	608.00
0.0900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	618.00
0.1700	0.00	0.00	0.00	0.00	0.00	0.00	608.00	
0.2400	0.00	0.00	0.00	0.00	618.00			
0.3100	0.00	0.00	0.00	618.00				
0.4100	0.00	0.00	621.00					
0.5500	0.00	617.00						
0.7200	0.00	614.00						
0.9200	0.00	557.00						

THE TOTAL HEAT FLOW RATE IS -131.43440BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	588.00	555.00	544.00	550.00	560.00	536.00	511.00	511.00
0.0400	514.11	612.03	612.72	612.75	612.53	611.66	611.90	608.00
0.0900	614.59	612.93	613.76	613.71	613.33	612.81	613.43	618.00
0.1700	615.52	615.38	615.36	615.32	614.97	513.14	608.00	
0.2400	616.48	616.66	616.76	616.82	618.00			
0.3100	617.35	617.87	618.21	618.00				
0.4100	618.03	619.27	621.00					
0.5500	616.42	617.00						
0.7200	612.56	614.00						
0.9200	601.49	557.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 40/1000, POWER= 75 PER CENT

DISTANCE	0.00	0.13	0.25	0.34	0.50	0.56	0.63	0.68
0.0200	520.00	507.00	503.00	494.00	481.00	485.00	490.00	490.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	651.00
0.0900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	661.00
0.1700	0.00	0.00	0.00	0.00	0.00	0.00	651.00	
0.2400	0.00	0.00	0.00	0.00	662.00			
0.3100	0.00	0.00	0.00	663.00				
0.4100	0.00	0.00	661.00					
0.5500	0.00	662.00						
0.7200	0.00	660.00						
0.9200	0.00	594.00						

THE TOTAL HEAT FLOW RATE IS -232.58840BTU/HR

DISTANCE	0.00	0.13	0.25	0.34	0.50	0.56	0.63	0.68
0.0200	520.00	507.00	503.00	494.00	481.00	485.00	490.00	490.00
0.0400	649.41	649.49	649.79	650.12	650.47	650.90	652.85	651.00
0.0900	651.36	651.67	652.01	652.49	653.04	653.42	655.32	661.00
0.1700	654.32	654.89	655.44	656.28	656.95	655.38	651.00	
0.2400	656.51	657.32	658.16	659.70	662.00			
0.3100	658.24	659.20	660.28	663.00				
0.4100	659.68	660.61	661.00					
0.5500	659.78	662.00						
0.7200	652.68	660.00						
0.9200	610.92	594.00						

Table 6 (continued)

Valve Temperature Profiles

CERAMIC = 40/1000, POWER= 50 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	549.00	537.00	533.00	535.00	538.00	535.00	529.00	529.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	588.00
0.0900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	598.00
0.1700	0.00	0.00	0.00	0.00	0.00	0.00	588.00	
0.2400	0.00	0.00	0.00	0.00	598.00			
0.3100	0.00	0.00	0.00	598.00				
0.4100	0.00	0.00	598.00					
0.5500	0.00	597.00						
0.7200	0.00	597.00						
0.9200	0.00	567.00						

THE TOTAL HEAT FLOW RATE IS -120.05590BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	549.00	537.00	533.00	535.00	538.00	535.00	529.00	529.00
0.0400	592.95	592.73	592.71	592.84	592.63	592.24	592.77	588.00
0.0900	593.61	593.56	593.62	593.72	593.46	593.11	593.73	598.00
0.1700	594.72	594.87	595.03	595.24	595.32	593.21	588.00	
0.2400	595.59	595.89	596.19	596.71	598.00			
0.3100	596.29	596.73	597.17	598.00				
0.4100	596.81	597.40	598.00					
0.5500	596.33	597.00						
0.7200	593.57	597.00						
0.9200	574.66	567.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 40/1000, POWER= 25 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	498.00	475.00	473.00	469.00	462.00	446.00	430.00	430.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	608.00
0.0900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	618.00
0.1700	0.00	0.00	0.00	0.00	0.00	0.00	608.00	
0.2400	0.00	0.00	0.00	0.00	618.00			
0.3100	0.00	0.00	0.00	618.00				
0.4100	0.00	0.00	610.00					
0.5500	0.00	612.00						
0.7200	0.00	605.00						
0.9200	0.00	582.00						

THE TOTAL HEAT FLOW RATE IS -220.314308TU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	498.00	475.00	473.00	469.00	462.00	446.00	430.00	430.00
0.0400	604.73	604.97	605.55	606.52	607.68	607.84	609.47	608.00
0.0900	606.34	606.99	607.56	608.61	609.89	610.29	612.18	618.00
0.1700	608.59	609.48	610.42	611.54	613.40	612.20	608.00	
0.2400	609.96	611.06	612.37	614.96	613.00			
0.3100	610.69	611.74	613.25	618.00				
0.4100	610.62	610.82	610.00					
0.5500	610.12	612.00						
0.7200	603.39	605.00						
0.9200	588.17	582.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 40/1000, POWER= 00 PER CENT

DISTANCE	0.00	0.19	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	626.00	619.00	617.00	598.00	570.00	565.00	560.00	560.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	712.00
0.0900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	722.00
0.1700	0.00	0.00	0.00	0.00	0.00	0.00	712.00	
0.2400	0.00	0.00	0.00	0.00	722.00			
0.3100	0.00	0.00	0.00	722.00				
0.4100	0.00	0.00	721.00					
0.5500	0.00	720.00						
0.7200	0.00	700.00						
0.9200	0.00	675.00						

THE TOTAL HEAT FLOW RATE IS -199.10940BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	626.00	619.00	617.00	598.00	570.00	565.00	560.00	560.00
0.0400	712.66	712.77	712.92	712.73	712.37	712.54	714.15	712.00
0.0900	713.96	714.21	714.38	714.48	714.53	714.78	716.48	722.00
0.1700	715.93	716.39	716.75	717.28	717.77	716.40	712.00	
0.2400	717.34	718.05	718.67	719.77	722.00			
0.3100	718.33	719.33	720.19	722.00				
0.4100	718.65	720.19	721.00					
0.5500	716.09	720.00						
0.7200	700.17	700.00						
0.9200	682.26	675.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 00/1000, POWER= 100 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	563.00	555.00	558.00	559.00	561.00	554.00	547.00	547.00
0.0200	0.00	0.00	0.00	0.00	0.00	0.00	0.00	685.00
0.0500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	695.00
0.1300	0.00	0.00	0.00	0.00	0.00	0.00	685.00	
0.2000	0.00	0.00	0.00	0.00	697.00			
0.2700	0.00	0.00	0.00	700.00				
0.3700	0.00	0.00	705.00					
0.5100	0.00	655.00						
0.6800	0.00	685.00						
0.9800	0.00	674.00						

THE TOTAL HEAT FLOW RATE IS -3197.26300BTU/HR

DISTANCE	0.00	0.19	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	563.00	555.00	558.00	559.00	561.00	554.00	547.00	547.00
0.0200	563.00	555.00	558.00	559.00	561.00	554.00	547.00	685.00
0.0500	582.95	582.60	584.01	587.77	597.86	605.66	632.28	695.00
0.1300	615.04	619.02	623.61	632.13	652.60	662.57	685.00	
0.2000	640.53	647.46	654.76	667.91	697.00			
0.2700	661.60	670.99	680.92	700.00				
0.3700	682.62	692.92	705.00					
0.5100	690.36	695.00						
0.6800	684.77	685.00						
0.9800	677.09	674.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 00/1000, POWER= 75 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	548.00	529.00	523.00	521.00	517.00	525.00	533.00	533.00
0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	650.00
0.0500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	660.00
0.1300	0.00	0.00	0.00	0.00	0.00	0.00	650.00	
0.2000	0.00	0.00	0.00	0.00	667.00			
0.2700	0.00	0.00	0.00	675.00				
0.3700	0.00	0.00	675.00					
0.5100	0.00	670.00						
0.6800	0.00	652.00						
0.8800	0.00	637.00						

THE TOTAL HEAT FLOW RATE IS -3118.67100BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	548.00	529.00	523.00	521.00	517.00	525.00	533.00	533.00
0.0000	548.00	525.00	523.00	521.00	517.00	525.00	533.00	650.00
0.0500	561.50	552.24	550.65	552.13	560.11	573.64	603.72	660.00
0.1300	589.01	585.09	592.48	600.98	619.00	626.54	650.00	
0.2000	613.01	618.28	625.40	639.12	667.00			
0.2700	633.80	642.39	652.79	675.00				
0.3700	654.55	664.39	675.00					
0.5100	663.33	670.00						
0.6800	652.42	652.00						
0.8800	641.43	637.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 00/1000, POWER = 25 PER CENT

DISTANCE	0.00	0.13	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	559.00	561.00	561.00	563.00	567.00	565.00	564.00	564.00
0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	534.00
0.0500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	544.00
0.1300	0.00	0.00	0.00	0.00	0.00	0.00	534.00	
0.2000	0.00	0.00	0.00	0.00	545.00			
0.2700	0.00	0.00	0.00	546.00				
0.3700	0.00	0.00	544.00					
0.5100	0.00	537.00						
0.6800	0.00	526.00						
0.8800	0.00	515.00						

THE TOTAL HEAT FLOW RATE IS 449.00360BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	560.00	561.00	561.00	563.00	567.00	565.00	564.00	564.00
0.0000	560.00	561.00	561.00	563.00	567.00	565.00	564.00	534.00
0.0500	557.91	558.40	558.50	559.25	559.25	556.76	550.52	544.00
0.1300	554.20	554.23	554.00	553.47	549.83	545.01	534.00	
0.2000	550.91	550.77	550.36	549.31	545.00			
0.2700	547.72	547.61	547.24	546.00				
0.3700	543.31	543.60	544.00					
0.5100	536.50	537.00						
0.6800	526.71	526.00						
0.8800	518.36	515.00						

Table 6 (continued)
Valve Temperature Profiles

CERAMIC = 00/1000, POWER= 00 PER CENT

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	588.00	546.00	532.00	531.00	530.00	522.00	514.00	514.00
0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	580.00
0.0500	0.00	0.00	0.00	0.00	0.00	0.00	0.00	590.00
0.1300	0.00	0.00	0.00	0.00	0.00	0.00	580.00	
0.2000	0.00	0.00	0.00	0.00	601.00			
0.2700	0.00	0.00	0.00	613.00				
0.3700	0.00	0.00	600.00					
0.5100	0.00	583.00						
0.6800	0.00	591.00						
0.9800	0.00	555.00						

THE TOTAL HEAT FLOW RATE IS -1579.25300BTU/HR

DISTANCE	0.00	0.18	0.25	0.34	0.50	0.56	0.63	0.68
0.0000	588.00	546.00	532.00	531.00	530.00	522.00	514.00	514.00
0.0000	598.00	546.00	532.00	531.00	530.00	522.00	514.00	580.00
0.0500	577.95	554.27	547.63	546.60	547.29	547.45	557.72	590.00
0.1300	577.04	565.70	568.46	570.96	575.36	574.50	580.00	
0.2000	581.43	580.83	584.23	591.55	601.00			
0.2700	586.18	585.68	596.43	613.00				
0.3700	595.33	593.57	600.00					
0.5100	584.92	583.00						
0.6800	585.93	591.00						
0.8900	563.90	555.00						

Table 6 (continued)
Valve Temperature Profiles

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THE THERMAL CONDUCTIVITY FOR THE INSULATION IS  0.40000
THE THERMAL CONDUCTIVITY FOR THE METAL IS  33.00000
THE TOLERANCE FOR CHANGE IN AVG ELEMENT TEMP BETWEEN ITERATIONS IS   0.10000
THE TOLERANCE FOR MAXIMUM CHANGE IN TEMPERATURE IS   0.10000
NOTE  THE UPPER LEFT HAND CORNER IS THE TOP CENTER OF THE PISTON OR VALVE.
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Table 6 (continued)

Valve Temperature Profiles

CERAMIC = 100/1000, POWER= 100 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	540.00	530.00	520.00	541.00	562.00	578.00	606.00	548.00	500.00	500.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	241.00
0.2900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	231.00
0.4700	311.00	310.00	309.00	307.00	308.00	309.00	298.00	278.00	0.00	220.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							268.00	0.00	195.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							268.00	0.00	136.80

THE TOTAL HEAT FLOW RATE IS 736.440508TU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	540.00	530.00	520.00	541.00	562.00	578.00	606.00	548.00	500.00	500.00
0.1000	318.53	318.02	317.24	317.11	317.16	314.75	303.88	281.14	247.78	241.00
0.2900	313.36	313.14	312.58	311.55	311.52	308.69	296.93	274.99	241.98	231.00
0.4700	311.00	310.00	309.00	307.00	308.00	309.00	298.00	273.00	234.81	220.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							268.00	211.79	195.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							268.00	183.58	136.80

THE NUMBER OF ITERATIONS WAS 13

Table 7

Piston Temperature Profiles

CERAMIC = 100/1000, POWER= 75 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	622.00	547.00	472.00	475.00	477.00	568.00	516.00	500.00	495.00	495.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	221.00
0.2900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	210.00
0.4700	274.00	273.00	272.00	270.00	270.00	271.00	271.00	251.00	0.00	198.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							241.00	0.00	175.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							241.00	0.00	128.00

THE TOTAL HEAT FLOW RATE IS 705.79390BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	622.00	547.00	472.00	475.00	477.00	568.00	516.00	500.00	495.00	495.00
0.1000	284.63	282.49	279.83	279.20	278.86	280.37	273.25	254.18	225.68	221.00
0.2900	276.80	276.40	275.46	274.68	274.29	273.74	267.66	248.52	219.48	210.00
0.4700	274.00	273.00	272.00	270.00	270.00	271.00	271.00	251.00	211.76	198.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							241.00	190.60	175.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							241.00	167.68	128.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 100/1000, POWER= 50 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	483.00	481.00	478.00	479.00	479.00	484.00	480.00	481.00	478.00	478.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	186.00
0.2900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	181.00
0.4700	217.00	216.00	216.00	216.00	217.00	218.00	220.00	200.00	0.00	175.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							190.00	0.00	164.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							190.00	0.00	116.00

THE TOTAL HEAT FLOW RATE IS 792.86980BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	483.00	481.00	478.00	479.00	479.00	484.00	480.00	481.00	478.00	478.00
0.1000	227.66	227.49	227.46	227.59	227.78	227.56	224.17	209.71	193.70	186.00
0.2900	221.73	221.65	221.69	221.80	221.99	221.65	218.28	203.46	187.15	181.00
0.4700	217.00	216.00	216.00	216.00	217.00	218.00	220.00	200.00	181.62	175.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							190.00	168.44	164.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							190.00	145.46	116.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 100/1000, POWER= 25 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	538.00	507.00	475.00	480.00	484.00	476.00	475.00	476.00	475.00	475.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	167.00
0.2900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	163.00
0.4700	196.00	195.00	195.00	194.00	195.00	196.00	196.00	176.00	0.00	159.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							166.00	0.00	151.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							166.00	0.00	118.00

THE TOTAL HEAT FLOW RATE IS 740.26390BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	538.00	507.00	475.00	480.00	484.00	476.00	475.00	476.00	475.00	475.00
0.1000	208.71	207.78	206.80	206.70	206.80	205.87	201.77	188.05	175.35	167.00
0.2900	201.08	200.89	200.63	200.40	200.42	199.65	195.48	181.42	168.45	163.00
0.4700	196.00	195.00	195.00	194.00	195.00	196.00	196.00	176.00	163.62	159.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							166.00	153.38	151.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							166.00	137.52	118.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)
Piston Temperature Profiles

CERAMIC = 100/1000, POWER= 0 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	497.00	454.00	490.00	486.00	481.00	476.00	476.00	476.00	475.00	475.00
0.1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	146.00
0.2900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	142.00
0.4700	177.00	176.00	176.00	175.00	176.00	177.00	176.00	156.00	0.00	138.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							146.00	0.00	130.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							146.00	0.00	115.00

THE TOTAL HEAT FLOW RATE IS 785.21850BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	497.00	454.00	490.00	486.00	481.00	476.00	476.00	476.00	475.00	475.00
0.1000	189.48	185.26	189.00	188.64	188.44	187.40	182.74	168.66	155.26	146.00
0.2900	182.36	192.24	182.07	181.79	181.71	180.76	175.99	161.59	147.89	142.00
0.4700	177.00	176.00	176.00	175.00	176.00	177.00	176.00	156.00	142.99	138.00
0.9160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							146.00	133.82	130.00
1.1500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							146.00	126.39	115.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 70/1000, POWER= 100 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	533.00	532.00	530.00	528.00	527.00	533.00	527.00	525.00	527.00	527.00
0.0700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	264.00
0.2600	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	250.00
0.4400	319.00	316.00	317.00	316.00	317.00	318.00	318.00	298.00	0.00	236.00
0.8860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							288.00	0.00	207.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							288.00	0.00	142.00

THE TOTAL HEAT FLOW RATE IS 888.24020BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	533.00	532.00	530.00	528.00	527.00	533.00	527.00	525.00	527.00	527.00
0.0700	330.06	329.91	329.46	329.04	328.88	327.91	321.87	302.26	269.82	264.00
0.2600	323.42	323.28	322.86	322.50	322.36	321.16	315.12	294.94	261.35	250.00
0.4400	319.00	318.00	317.00	316.00	317.00	318.00	318.00	298.00	252.03	236.00
0.8860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							288.00	225.66	207.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							288.00	194.12	142.00

THE NUMBER OF ITERATIONS WAS 20

Table 7 (continued)
Piston Temperature Profiles

CERAMIC = 70/1000, POWER= 75 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	532.00	540.00	547.00	566.00	584.00	514.00	515.00	514.00	516.00	516.00
0.0700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	234.00
0.2600	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	221.00
0.4400	285.00	284.00	284.00	283.00	283.00	283.00	284.00	264.00	0.00	209.00
0.8860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							254.00	0.00	183.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							254.00	0.00	138.00

THE TOTAL HEAT FLOW RATE IS 980.19750BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	532.00	540.00	547.00	566.00	584.00	514.00	515.00	514.00	516.00	516.00
0.0700	298.98	299.09	299.20	299.49	299.60	294.79	285.47	270.77	241.01	234.00
0.2600	291.25	291.17	291.05	290.72	290.24	287.58	282.05	262.77	231.96	221.00
0.4400	285.00	284.00	284.00	283.00	283.00	283.00	284.00	264.00	223.32	209.00
0.8860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							254.00	200.19	183.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							254.00	178.11	138.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 70/1000, POWER= 50 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	520.00	528.00	535.00	533.00	532.00	528.00	522.00	522.00	521.00	521.00
0.0700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	204.00
0.2600	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	194.00
0.4400	246.00	245.00	245.00	244.00	244.00	245.00	245.00	225.00	0.00	183.00
0.8860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							215.00	0.00	162.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							215.00	0.00	135.00

THE TOTAL HEAT FLOW RATE IS 1082.12600BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	520.00	528.00	535.00	533.00	532.00	528.00	522.00	522.00	521.00	521.00
0.0700	261.50	261.61	261.67	261.20	260.79	259.46	254.14	237.19	213.28	204.00
0.2500	252.94	252.85	252.68	252.26	251.87	250.63	245.33	227.82	203.16	194.00
0.4400	246.00	245.00	245.00	244.00	244.00	245.00	245.00	225.00	194.31	183.00
0.8860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							215.00	175.41	162.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							215.00	161.91	135.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)
Piston Temperature Profiles

CERAMIC = 70/1000. POWER= 25 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	568.00	551.00	534.00	550.00	565.00	568.00	562.00	560.00	558.00	558.00
0.0700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	183.00
0.2600	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	175.00
0.4400	215.00	214.00	214.00	213.00	213.00	214.00	215.00	195.00	0.00	167.00
0.6860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							185.00	0.00	151.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							185.00	0.00	119.00

THE TOTAL HEAT FLOW RATE IS 1283.71900BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	568.00	551.00	534.00	550.00	565.00	568.00	562.00	560.00	558.00	558.00
0.0700	234.55	233.81	233.06	233.38	233.76	233.15	228.88	213.59	195.13	183.00
0.2600	223.54	223.38	223.16	222.96	222.86	222.14	217.92	202.20	183.19	175.00
0.4400	215.00	214.00	214.00	213.00	213.00	214.00	215.00	195.00	174.78	167.00
0.6860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							185.00	158.85	151.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							185.00	143.18	119.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 70/1000, POWER= 0 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	522.00	542.00	562.00	561.00	560.00	575.00	566.00	566.00	565.00	565.00
0.0700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	156.00
0.2600	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	151.00
0.4400	177.00	176.00	176.00	175.00	175.00	176.00	176.00	156.00	0.00	146.00
0.8860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							146.00	0.00	136.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							146.00	0.00	114.00

THE TOTAL HEAT FLOW RATE IS 1395.23900BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	522.00	542.00	562.00	561.00	560.00	575.00	566.00	566.00	565.00	565.00
0.0700	197.38	197.94	198.55	198.23	197.98	197.90	193.70	180.71	170.09	156.00
0.2600	186.66	186.63	186.60	186.29	186.06	185.49	181.45	168.03	157.10	151.00
0.4400	177.00	176.00	176.00	175.00	175.00	176.00	176.00	156.00	149.30	146.00
0.8860	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							146.00	137.91	136.00
1.1200	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							146.00	127.11	114.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 40/1000, POWER= 100 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	524.00	521.00	517.00	518.00	518.00	503.00	495.00	510.00	510.00	510.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	286.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	269.00
0.4100	316.00	315.00	313.00	311.00	312.00	313.00	315.00	295.00	0.00	252.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							285.00	0.00	217.00
1.0300	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							285.00	0.00	131.00

THE TOTAL HEAT FLOW RATE IS 1320.81300BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	524.00	521.00	517.00	518.00	518.00	503.00	495.00	510.00	510.00	510.00
0.0400	334.30	333.94	332.98	332.41	332.19	330.33	326.05	311.43	289.40	286.00
0.2300	323.42	323.18	322.39	321.72	321.49	320.38	316.32	300.00	276.69	269.00
0.4100	316.00	315.00	313.00	311.00	312.00	313.00	315.00	295.00	263.37	252.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							285.00	231.05	217.00
1.0300	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							285.00	190.67	131.00

THE NUMBER OF ITERATIONS WAS 20

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 40/1000, POWER= 75 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	515.00	509.00	502.00	505.00	508.00	505.00	519.00	505.00	508.00	508.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	243.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	227.00
0.4100	259.00	258.00	258.00	258.00	258.00	259.00	259.00	239.00	0.00	211.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							229.00	0.00	179.00
1.0800	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							229.00	0.00	123.00

THE TOTAL HEAT FLOW RATE IS 1618.87500BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	515.00	509.00	502.00	505.00	508.00	505.00	519.00	505.00	508.00	508.00
0.0400	283.49	283.09	282.60	282.71	282.75	281.83	278.73	263.58	247.97	243.00
0.2300	270.20	270.09	269.97	269.91	269.78	268.98	264.89	249.68	233.00	227.00
0.4100	259.00	258.00	258.00	258.00	258.00	259.00	259.00	239.00	218.90	211.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							229.00	190.21	179.00
1.0800	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							229.00	163.54	123.00

THE NUMBER OF ITERATIONS WAS 20

Table 7 (continued)
Piston Temperature Profiles

CERAMIC = 40/1000, POWER= 50 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	510.00	511.00	511.00	515.00	519.00	506.00	514.00	518.00	503.00	503.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	215.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	203.00
0.4100	230.00	229.00	229.00	228.00	228.00	229.00	229.00	209.00	0.00	190.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							199.00	0.00	165.00
1.0300	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							199.00	0.00	118.00

THE TOTAL HEAT FLOW RATE IS 1769.41900BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	510.00	511.00	511.00	515.00	519.00	506.00	514.00	518.00	503.00	503.00
0.0400	257.09	257.08	256.93	256.85	256.83	255.14	251.86	238.87	224.94	215.00
0.2300	242.56	242.47	242.30	241.99	241.74	240.70	236.76	222.79	208.93	203.00
0.4100	230.00	229.00	229.00	228.00	228.00	229.00	229.00	209.00	195.77	190.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							199.00	172.27	165.00
1.0300	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							199.00	149.92	118.00

THE NUMBER OF ITERATIONS WAS 20

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 40/1000, POWER = 25 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	561.00	546.00	530.00	508.00	485.00	492.00	494.00	494.00	491.00	491.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	192.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	184.00
0.4100	204.00	203.00	202.00	201.00	202.00	203.00	203.00	183.00	0.00	175.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							173.00	0.00	158.00
1.0800	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							173.00	0.00	118.00

THE TOTAL HEAT FLOW RATE IS 1780.29100BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	561.00	546.00	530.00	508.00	485.00	492.00	494.00	494.00	491.00	491.00
0.0400	236.91	235.77	234.17	232.21	230.53	230.33	226.98	214.89	205.81	192.00
0.2300	218.21	217.92	217.13	216.33	215.88	215.27	211.61	198.82	189.39	184.00
0.4100	204.00	203.00	202.00	201.00	202.00	203.00	203.00	183.00	178.00	175.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							173.00	160.35	158.00
1.0800	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							173.00	141.44	118.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 40/1000, POWER= 0 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	498.00	461.00	423.00	449.00	475.00	473.00	480.00	485.00	484.00	484.00
0.0400	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	159.00
0.2300	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	154.00
0.4100	163.00	162.00	162.00	162.00	163.00	164.00	165.00	145.00	0.00	148.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							135.00	0.00	137.00
1.0800	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							135.00	0.00	111.00

THE TOTAL HEAT FLOW RATE IS 1869.32100BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	498.00	461.00	423.00	449.00	475.00	473.00	480.00	485.00	484.00	484.00
0.0400	194.23	191.95	189.75	191.69	193.79	193.74	191.76	181.43	176.55	159.00
0.2300	176.71	176.46	176.33	176.87	177.60	177.66	175.16	163.95	158.85	154.00
0.4100	163.00	162.00	162.00	162.00	163.00	164.00	165.00	145.00	148.34	148.00
0.8560	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							135.00	135.54	137.00
1.0800	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							135.00	123.18	111.00

THE NUMBER OF ITERATIONS WAS 19

Table 7 (continued)
Piston Temperature Profiles

CERAMIC = 00/1000, POWER= 100 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	520.00	515.00	510.00	517.00	523.00	523.00	556.00	562.00	560.00	560.00
0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	281.00
0.1900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	265.00
0.3700	309.00	309.00	307.00	306.00	307.00	308.00	309.00	289.00	0.00	250.00
0.8160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							279.00	0.00	218.00
1.0500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							279.00	0.00	142.00

THE TOTAL HEAT FLOW RATE IS 16203.26000BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	520.00	515.00	510.00	517.00	523.00	523.00	556.00	562.00	560.00	560.00
0.0000	520.00	515.00	510.00	517.00	523.00	523.00	556.00	562.00	560.00	281.00
0.1900	409.91	408.47	408.17	409.84	411.98	414.56	422.60	407.50	347.61	265.00
0.3700	309.00	308.00	307.00	306.00	307.00	308.00	309.00	289.00	272.61	250.00
0.8160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							279.00	231.67	218.00
1.0500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							279.00	194.29	142.00

THE NUMBER OF ITERATIONS WAS 21

Table 7 (continued)

Piston Temperature Profiles

AD-A096 762 OKLAHOMA STATE UNIV STILLWATER DIV OF ENGINEERING F/G 21/7
CHARACTERIZATION OF HEAT TRANSFER IN CERAMIC COATED INTERNAL CO--ETC(U)
FEB 81 R G MURRAY, N E HOECKER DAAG29-79-G-0021
UNCLASSIFIED ARO-157892.-E NL

2 of 2

END
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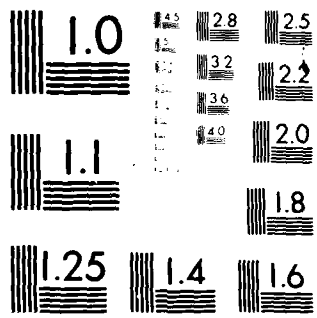

MICROCOPY RESOLUTION TEST CHART

CERAMIC = 00/1000, POWER= 75 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	521.00	527.00	532.00	536.00	540.00	555.00	550.00	539.00	537.00	537.00
0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	250.00
0.1900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	239.00
0.3700	276.00	275.00	274.00	272.00	273.00	275.00	274.00	254.00	0.00	227.00
0.8160	UUUUUUUUUULLUUUUUUUUUUUUUULULUUUUUUUUUUUUULUUUUUUUUUUUUUULUUU							244.00	0.00	204.00
1.0500	UUUUUUUUUUULLUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							244.00	0.00	130.00

THE TOTAL HEAT FLOW RATE IS 17780.42000BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	521.00	527.00	532.00	536.00	540.00	555.00	550.00	539.00	537.00	537.00
0.0700	521.00	527.00	532.00	536.00	540.00	555.00	550.00	539.00	537.00	250.00
0.1900	398.54	399.16	400.41	401.74	403.72	408.37	402.77	380.54	322.14	239.00
0.3700	276.00	275.00	274.00	272.00	273.00	275.00	274.00	254.00	246.99	227.00
0.5160	UUUUUUUUUUULULUUULUUUUUUUUULUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							244.00	211.87	204.00
1.0500	UUUUUUUUUUULLUUULUUUUUUUUULUULUULUUUUUUULUUUUUUUUUUUUULUUU							244.00	175.71	130.00

THE NUMBER OF ITERATIONS WAS 21

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 00/1000, POWER= 50 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	560.00	559.00	558.00	562.00	566.00	555.00	564.00	537.00	535.00	535.00
0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	235.00
0.1900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	227.00
0.3700	243.00	242.00	241.00	240.00	240.00	241.00	242.00	222.00	0.00	218.00
0.8160	UUUUUUUUUUULUUUUUUUUUUUUULUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							212.00	0.00	201.00
1.0500	UUUUUUUUUUULLUUULUUUUUUULLUUUUULUUUUUUUULUUUUUUUUUUUUUUU							212.00	0.00	123.00

THE TOTAL HEAT FLOW RATE IS 19763.42000BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	560.00	559.00	558.00	562.00	566.00	555.00	564.00	537.00	535.00	535.00
0.0000	560.00	559.00	558.00	562.00	566.00	555.00	564.00	537.00	535.00	235.00
0.1900	396.27	396.14	396.04	396.63	397.02	393.72	391.26	365.33	311.19	227.00
0.3700	243.00	242.00	241.00	240.00	240.00	241.00	242.00	222.00	232.86	218.00
0.8160	UUUUUUUUUUUULUUUUUUUUUUUUULUUUUUUUUUUUUULUUUULUUUUUUULLUU							212.00	200.75	201.00
1.0500	UUUUUULUULLLLUUUULUUUUUUUULUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							212.00	162.87	123.00

THE NUMBER OF ITERATIONS WAS 21

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 00/1000, POWER= 25 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	517.00	535.00	552.00	560.00	568.00	560.00	558.00	561.00	559.00	559.00
0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	210.00
0.1900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	201.00
0.3700	215.00	214.00	214.00	213.00	214.00	215.00	215.00	195.00	0.00	192.00
0.8160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							185.00	0.00	173.00
1.0500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							185.00	0.00	121.00

THE TOTAL HEAT FLOW RATE IS 22136.69000BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	517.00	535.00	552.00	560.00	568.00	560.00	558.00	561.00	559.00	559.00
0.0000	517.00	535.00	552.00	560.00	568.00	560.00	558.00	561.00	559.00	210.00
0.1900	373.20	378.21	379.27	382.01	384.14	381.90	377.38	359.27	298.69	201.00
0.3700	215.00	214.00	214.00	213.00	214.00	215.00	215.00	195.00	208.87	192.00
0.8160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							185.00	174.95	173.00
1.0500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							185.00	149.08	121.00

THE NUMBER OF ITERATIONS WAS 21

Table 7 (continued)

Piston Temperature Profiles

CERAMIC = 00/1000, POWER= 0 PER CENT

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	507.00	516.00	525.00	523.00	520.00	520.00	519.00	517.00	515.00	515.00
0.0900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	169.00
0.1900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	163.00
0.3700	177.00	176.00	176.00	175.00	176.00	177.00	177.00	157.00	0.00	158.00
0.8160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							147.00	0.00	146.00
1.0500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							147.00	0.00	115.00

THE TOTAL HEAT FLOW RATE IS 21862.84000BTU/HR

DISTANCE	0.00	0.11	0.25	0.38	0.50	0.75	1.00	1.25	1.50	1.60
0.0000	507.00	516.00	525.00	523.00	520.00	520.00	519.00	517.00	515.00	515.00
0.0900	507.00	516.00	525.00	523.00	520.00	520.00	519.00	517.00	515.00	169.00
0.1900	342.16	343.00	344.33	343.94	343.37	342.67	336.43	319.05	259.72	163.00
0.3700	177.00	176.00	176.00	175.00	176.00	177.00	177.00	157.00	173.59	158.00
0.8160	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							147.00	146.07	146.00
1.0500	UUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUUU							147.00	130.28	115.00

THE NUMBER OF ITERATIONS WAS 21

STATEMENTS EXECUTED= 158470

CORE USAGE OBJECT CODE= 8248 BYTES,ARRAY AREA= 2464 BYTES,TOTAL AREA AVAILABLE= 133120 BYTES

DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 0

COMPILE TIME= 0.15 SEC,EXECUTION TIME= 3.45 SEC, 21.15.09 THURSDAY 8 JAN 81 WATFIV - MAR 1980 V2L0

C$STOP

Table 7 (continued) - Piston Temperature Profiles

```
THE THERMAL CONDUCTIVITY FOR THE INSULATION IS  0.40000
THE THERMAL CONDUCTIVITY FOR THE METAL IS  33.00000
THE TOLERANCE FOR CHANGE IN AVG ELEMENT TEMP BETWEEN ITERATIONS IS   0.10000
THE TOLERANCE FOR MAXIMUM CHANGE IN TEMPERATURE IS   0.10000
NOTE  THE UPPER LEFT HAND CORNER IS THE TOP CENTER OF THE PISTON OR VALVE.
```

Table 7 (continued)
Piston Temperature Profiles

Table 8

INFRARED TO THERMOCOUPLE HEAT FLOW

CERAMIC THICKNESS INCHES	PERCENT POWER	HEAT FLOW BTU/HR	
		PISTON	VALVE
.10	100	736	35
.07	100	888	61
.04	100	1321	131
.00	100	16203	3197
.10	75	706	27
.07	75	980	153
.04	75	1619	233
.00	75	17780	3118
.10	50	703	78
.07	50	1082	158
.04	50	1769	120
.00	50	19763	3203
.10	25	740	111
.07	25	1284	133
.04	25	1780	220
.00	25	22137	449
.10	MIN	789	116
.07	MIN	1399	160
.04	MIN	1869	199
.00	MIN	21863	1579

Table 9

THERMOCOUPLE TO THERMOCOUPLE HEAT FLOW

CERAMIC THICKNESS INCHES	PERCENT POWER	PISTON HEAT FLOW BTU PER HOUR
.10	100	2311.
.07	100	2180.
.04	100	2844.
.00	100	2806.
.10	75	1951.
.07	75	2128.
.04	75	2592.
.00	75	2813.
.10	50	2352.
.07	50	1832.
.04	50	2186.
.00	50	3646.
.10	25	1632.
.07	25	1502.
.04	25	1936.
.00	25	2696.
.10	MIN	935.
.07	MIN	1159.
.04	MIN	1254.
.00	MIN	1521.

durance test performed under an earlier grant.

The purpose of this test was to identify failure modes of zirconium oxide coatings in internal combustion engine combustion chambers. Three types of metal are commonly found in engines: aluminum, cast iron and steel. It was, therefore, desirable to test the behavior of all three materials with various coating thicknesses.

To satisfy the test criteria, a 1952 Chevrolet 216 cubic inch, 6 cylinder engine was selected. This particular engine was chosen since both cast iron and aluminum pistons are available. This engine was remanufactured and fitted with new oversize pistons, three, of which were cast iron and three were aluminum. Prior to assembly, the pistons were coated with a nominal 0.03, 0.06 and 0.10 inch coating of yttrium stabilized zirconium oxide. The piston tops were machined to reduce thicknesses so that all pistons would have the same height after coating. The valves and combustion chamber walls were also coated with ceramic to the above thicknesses. Figures 29 and 30 portray typical preassembly component details.

The engine was assembled and operated on a simulated driving cycle for a first 1000 hours. This driving cycle consisted of 23 hours plus 55 minutes at 2000 rpm at 30% of maximum power, followed by 5 minutes at full power also at 2000 rpm. No operational data, except time, was recorded.

Following the first 1000 hours, the engine was disassembled and inspected. No significant coating degradation was found, except on the perimeter of the intake valves; here, most of the ceramic had separated.

The second 1000 hours test proceeded after an engine overhaul that included new piston rings and bearings.

The second test was conducted with the same simulated driving cycle. Forty hours into the second 1000 hour test, a generator failure resulted in the fan belt failure. This, in turn, caused high engine temperature. A coincidental failure of the safety switch allowed the engine to run to seizure. Following this problem, the engine was again overhauled and placed into service with all of the original ceram-

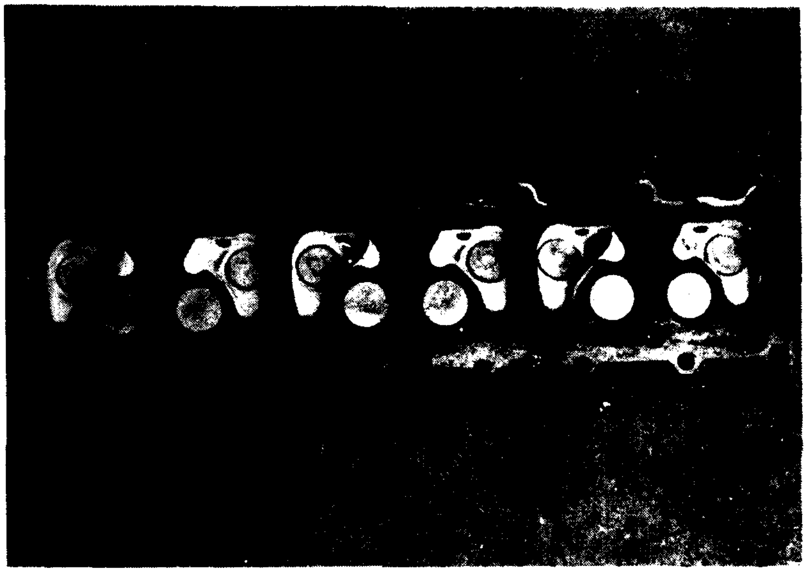

Figure 29: Endurance Engine Cylinder Head

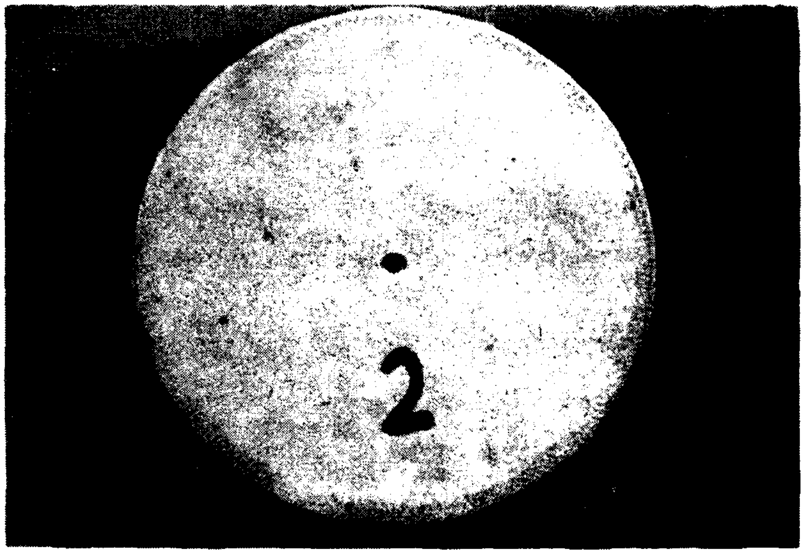

Figure 30: Endurance Engine Piston

ic surfaces.

After 2000 hours of exposure, the engine was disassembled and inspected. As before, no significant problems were observed with the coating. The piston surfaces had some heat cracks and some feathering on the perimeter; no additional separations had occurred, however, since the first 1000 hours.

Figures 31-36 portray typical surfaces after 2000 hours of operation. Note that some surfaces seem abraded and, in some cases, this condition goes to the base metal. This abrasion is the result of glass bead blasting that not only removed carbon deposits, but also, the ceramic coating. The coating was secure and in place prior to blasting.

SUMMARY AND CONCLUSIONS

The preceding document outlines details of a study of heat transfer, temperature profiles and endurance for ceramic coated internal combustion engine parts. Such parts offer significant promise in the advancement of engine technology.

The first objective of the study was to create a mathematical model that could predict heat transfer and temperatures within coated pistons and valves. This model was developed, and is presented, in computer card format. With this model, a design engineer should be able to optimize such parts for any engine application.

The second objective was to measure operational temperatures of a piston and a valve with various thicknesses of coating at various power levels. To do this, two rather novel techniques were used. Thermocouples were installed in moving crankcase piston surfaces and the signal was routed by hard wire techniques out of the crankcase. This procedure was quite successful and produced excellent results.

The second technique incorporated fiber optic probes to measure combustion chamber surface temperatures using infrared detectors. This procedure produced poor results in spite of extensive calibration efforts. It is believed that this method can be made to work, and with additional development will be an extremely valuable tool for

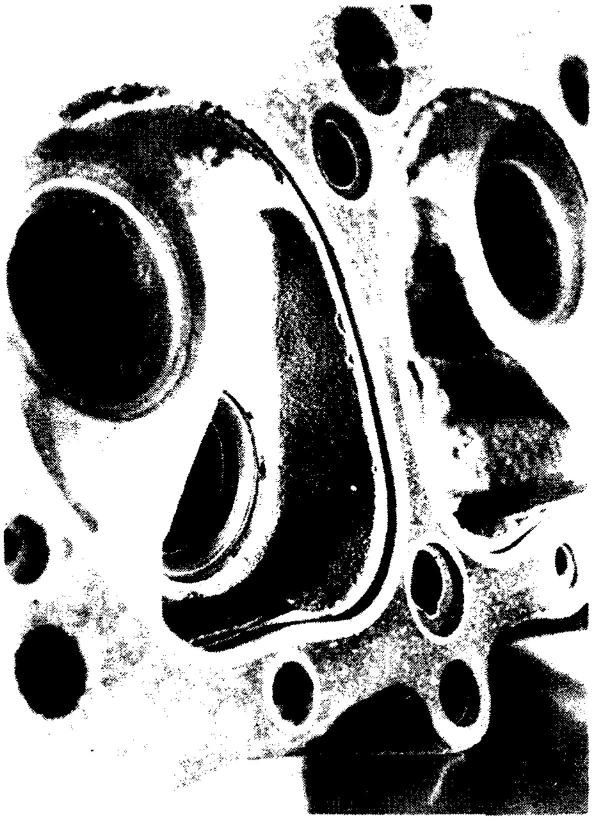

Figure 31:

Cylinder Head Surfaces

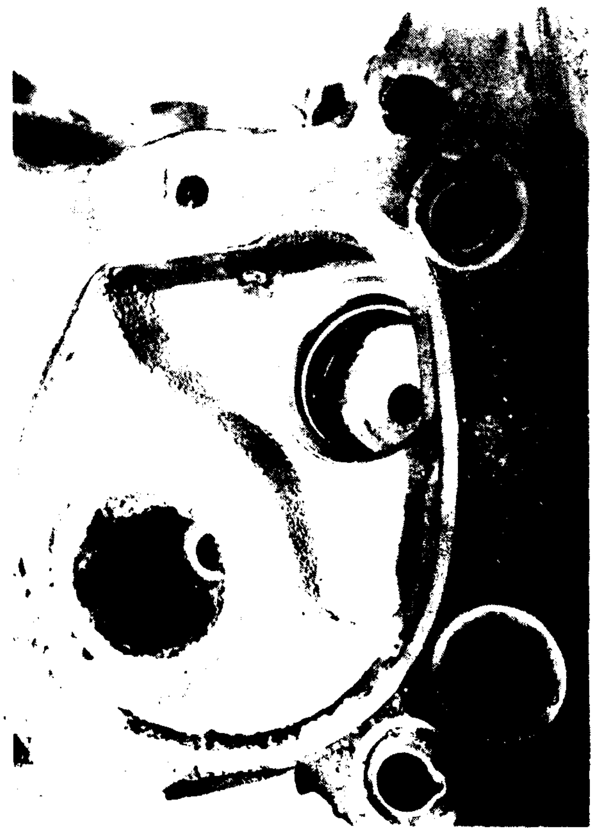

Figure 32:

Cylinder Head Surfaces

Figure 33: Valve Surfaces

Figure 34: Valve Surfaces

Figure 35: Piston Surfaces

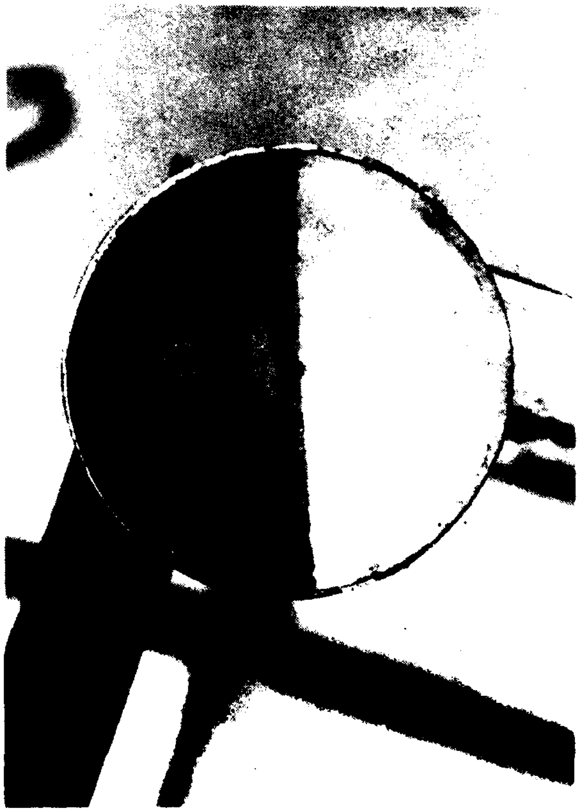

Figure 36: Piston Surfaces

engine research.

It is recommended that additional efforts be undertaken to perfect the fiber optics, infrared technique.

The third objective was the continuation of an earlier 1000 hour endurance test of ceramic coated engine parts. This final test added a second 1000 hour of time to the existing engine. This effort proved without doubt that ceramic coated parts can endure the torturous environment of I-C engines without significant degradation.

ACKNOWLEDGEMENT

The authors wish to express their appreciation to the U.S. Army research office for the opportunity to examine this most important area of engine technology.

They also wish to express their gratitude to the dedicated staff that made the project a success.

REFERENCES

1) Pachernegg, S.J., "Heat Flow in Engine Pistons", SAE paper No. 670928.

2) Ramchandan, M. and N.D. Whitehouse, "Heat Transfer in a Piston of a Four Stroke Diesel Engine", SAE paper No. 76007.

3) Roehrle, Manfred D., "Thermal Effects of Diesel Engine Pistons", SAE paper No. 780781.

4) Stotter, A., "Heat Transfer in Piston Cooling", SAE paper No. 660757.

5) IP, E.S., "Temperature Distribution in Diesel Engine Pistons", The Engineer, November 30, 1962.

6) Annand, W.J.D., "Heat Transfer in the Cylinders of Reciprocating Internal Combustion Engines", Proc. Instn. Mech. Engr., Vol. 177, No. 36, 1963.

7) "Diesel Engine Thermal Loading", SAE special publication No. 449.

8) Adams, J.A. and David F. Royers, Computer Aided Heat Transfer Analysis, McGraw-Hill, 1973.

Appendix 1

TPRL

THERMOPHYSICAL PROPERTIES RESEARCH LABORATORY

TPRL 194

Thermophysical Properties of a Coating

A Report to Oklahoma State University

by

R.E. Taylor and H. Groot

August, 1979

School of Mechanical Engineering

Purdue University, West Lafayette, Indiana

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Thermophysical Properties of a Coating

INTRODUCTION

Four duplicate samples of a zirconia coating on a steel sample were furnished by Dr. Murray of Oklahoma State University for thermal conductivity determinations. The samples were nominally 0.5 inch diameter and 0.1 inch thick with the steel comprising a little over one-half of the thickness. The basic approach to be used to determine the thermal conductivity "k" was to measure the thermal diffusivity, "α", specific heat "C_p" and density "d" since $k = \alpha C_p d$. The bulk densities were determined from mass and geometry measurements, the specific heat was measured using a differential scanning calorimeter, and the thermal diffusivity "α" was measured using the laser flash method. This technique for obtaining thermal conductivity is widely used and has the advantages of simple small sample size, and the elimation of the heat flux and temperature gradient measurements. These later measurements, combined with extraneous heat flows, are the primary resons why direct conductivity measurements are difficult and often yield poor results.

The Perkin-Elmer DSC II differential scanning calorimeter is used for routine determinations of specific heat up to 700° C. The differential heat required to heat the sample and a standard saphire specimen is measured. From the mass of the sample and the saphire and the known specific heat of saphire, the specific heat of the unknown can be calculated. A continuous recording of microcalories versus temperature is obtained during the experiment.

The flash method in which the front face of a small disc-shaped sample is subjected to a short laser burst and the resulting rear face temperature rise is recorded, is used in over 80% of the present thermal diffusivity measurements throughout the world. A highly developed apparatus exists at TPRL and we have been involved in an extensive program to evaluate the technique and broaden its uses. The apparatus consists of a Korad K2 laser, a high vacuum system including a bell jar with windows for viewing the sample, a tantalum tube heater surrounding a sample holding assembly, a spring-loaded thermocouple, appropriate biasing circuits, amplifers, A-D converters, crystal clocks, and a minicomputer-based digital data acquisition system capable of accurately taking data in the 40 microsecond and longer time domain. The computer controls the experiment, collects the data, calculates the results, and compared the raw data with the theoretical model. A typical visual display is shown in Figure 1. The raw data are given in Table 1 and the computations are given in Table 2. The vertical axis of Figure 1 is non-dimensional temperature rise (the temperature rise at anytime divided by the maximum rise). The horizontal axis is non-dimensional time (the time from the initiation of the laser pulse divided by the time to reach one-half of the maximum temperature rise). The solid curve represents the theoretical model and the points are the actual data. Note the close agreement between the experimental data and the mathematical model (Figure 1). The calculated results given in Table 2 were obtained from the computer output of Table 1. The column headed "ALPHA" are the diffusivity values ($cm^2\ sec^{-1}$) calculated assuming no finite pulse effect at various percent rises (PER). The column marked "VALUE" is the emf output corresponding to the percent rise and "TIME" represents the time in seconds from the initiation of the pulse until the rear face temperature rise reached the indicated percent value. The resulting values of α range from 0.00309 to 0.00321 between 10 and 80% of the temperature rise (Table 2) and the best value is 0.00320 $cm^2\ sec^{-1}$.

A special technique has been developed to measure the thermal diffusivity of one layer in intimate contact with a second layer. The half-time for the composite is measured and the rise curve is compared to the theoretical model in the usual fashion. In order to use this method, it is necessary to know the thicknesses, specific heats and densities of the two layers and the diffusivity of the second layer. Thus these properties were measured for the steel sample using a blank furnished by Dr. Murray. However, the rise curves for the composite samples did not follow the theoretical model, showing that interfacial contact resistance was present. A typical result is shown in Figure 2. Note the differences between the theoretical and experimental rise curves. Since the coatings were reasonably thick and could be removed from the substrate, the diffusivity of the free-standing coating was measured directly. In fact the visual display of Figure 1 and the data of Tables 1 and 2 are from the free-standing coating at room temperature.

RESULTS

The thermal diffusivity results for the coating and for the steel blank are given in Table 3. The diffusivity results for the coating are plotted in Figure 3. It was noted that the diffusivity values were unstable with time between 250 and 500° C and consequently measurements were made during the cooling cycle. These values were significantly less than those attained during initial heating.

The specific heat results for the coating and for the steel are given in Table 4 and plotted in Figure 4. A large peak was noted in the specific heat of the coating during the initial heating cycle (Figure 4). Thus the sample was rerun and the peak disappeared. This behavior occured over the same temperature range in which the diffusivity values were unstable (Figure 3) and the two phenomena are undoubtedly related.

Thermal conductivity values are calculated in Table 5 and plotted in Figure 5. No calculations were made between 300 and 500° C for the initial heating data as the specific heat and diffusivity values are certainly time-temperature dependent. However the cooling curve data (diffusivity) and second run data (specific heat) are representative of this material after temperature cycling to 500° C (1000° F).

With the knowledge of the thermal properties of both layers, it is possible to calculate the contact conductance for the two-layer case. These values ranged from 2.4 to 4.2 W cm^{-2} K^{-1} at room temperature for the three samples which were not sectioned.

The conductance values at higher temperatures or the changes caused by temperature cycling were not determined, although it would be possible to do so.

DISCUSSION

The changes in specific heat and thermal diffusivity (and consequently conductivity) noted during initial heating are undoubtedly due to the removal of a contaminant. We have often observed similar phenomena on other samples of materials which were significantly less than theoretical density. The sensitivity and accuracy of advanced computer-aided instrumentation and methods makes such changes readily discernable. However, unless one is interested in initial heating conditions, one should use the values generated during the cooling or second run curves.

TABLE 1

Experimental Data

OKLA. STATE UNIV. COATING AIR 23C

RUN # 1 ON 7/29/71; SAMPLE THICKNESS: 0. 1046 CM;

DURATION: 2. 200000 SEC. ; 0. 10000 SEC. BETWEEN TRAILING READINGS;

SHORT BASELINE; NO WILDNESS & SMOOTHING PERFORMED;

VOLTAGE	TIME
0. 47363159	0.
0. 50048699	44300.
0. 51269400	99610.
0. 55908060	154920.
0. 86181420	210230.
1. 27196937	265530.
1. 71630419	320830.
2. 20214277	376150.
2. 63915337	431460.
2. 95653536	486760.
3. 29589001	542060.
3. 60838919	597370.
3. 81102539	652680.
4. 00877878	708000.
4. 19676661	763300.
4. 37254734	818600.
4. 44823078	873910.
4 62157018	929220.
4. 65086698	984530.
4. 71922613	1039830.
4. 83885474	1095130.
4. 89500701	1150440.
4. 94627632	1205750.
5. 03172539	1261050.
5. 03172539	1316360.
5. 02928398	1371660.
5. 09520180	1426970.
5. 14158837	1482280.
5. 12449860	1537590.
5. 17088517	1592890.
5. 19285783	1648200.
5. 18553361	1703510.
5. 21238900	1758820.
5. 24168580	1814120.
5. 19285783	1869420.
5. 21971322	1924730.
5. 29783900	1980050.
5. 26121698	2035360.
5. 25145135	2090660.
5. 32957620	2145960.

INITIAL VOLTS	FINAL VOLTS
0. 48827999	5. 31004503
0. 48339720	5. 34666597
0. 51269400	5. 33690042
0. 55175639	5. 37596277
0. 48827999	5. 44920481
0. 50781119	5. 40525957
0. 47363159	5. 41502520
0. 48827999	5. 39549395
0. 54199080	5. 45408762
0. 52245959	5. 44920481
0. 55175639	5. 47361880
0. 49316280	5. 46385318
0. 51269400	5. 47361880
0. 51269400	5. 48338435
0. 59326019	5. 43455637
0. 58105319	5. 46873599
0. 54199080	5. 47361880
0. 51269400	5. 50779834
0. 52245959	5. 47361880
0. 50292839	5. 44432200
0. 49316280	5. 45408762
0. 55175639	5. 47361880
0. 54199080	5. 43455637
0. 48339720	5. 47361880
0. 49316280	5. 43455637
0. 51757679	5. 43455637
0. 53222519	5. 41502520
0. 50292839	5. 38572832
0. 53222519	5. 41502520
0. 52734240	5. 45408762
0. 49316280	5. 43455637
0. 48827999	5. 37596277
0. 50292839	5. 39549395
0. 50781119	5. 42967364

TABLE 2

Calculation of Thermal Diffusivity Values from Experimental Data

FLASH. FT
DATE: 7/29/71

OKLA. STATE UNIV. COATING AIR 23C

	VALUE	TIME(SEC)
BASELINE:	0.51312470	0.48661017
HALFMAXI:	2.92566239	0.47707939
MAXIMUM:	5.31561374	0.40919011

ALPHA	PER	VALUE	TIME(SEC)
0.00315968	10.0	0.99337363	0.22891539
0.00320300	20.0	1.47362291	0.28780382
0.00321028	25.0	1.71374678	0.31602185
0.00320497	30.0	1.95387184	0.34552216
0.00321118	33.3	2.11395442	0.36448961
0.00320276	40.0	2.43412017	0.40638661
0.00319483	50.0	2.91436910	0.47528982
0.00318505	60.0	3.39461803	0.55730617
0.00317127	66.7	3.71478438	0.62469685
0.00310430	70.0	3.87486696	0.67626202
0.00309831	75.0	4.11499202	0.74320042
0.00312028	80.0	4.35511648	0.81770813
0.00300381	90.0	4.83536422	1.10555171

TABLE 3

Thermal Diffusivity Results

Sample (No.)	Temp. (°C)	Temp. (°F)	Diffusivity (cm^2 sec^{-1})
Steel	23	73	0.183
Steel	93	199	0.163
Steel	204	399	0.137
Steel	315	599	0.113
Steel	426	799	0.094
Steel	537	999	0.078
Coating	23	73	0.00320
Coating	93	199	0.00305
Coating	204	399	0.00290
Coating	315	599	0.00274
Coating	426	799	0.00257
Coating	537	999	0.00241
Coating	426	799	0.00244
Coating	315	599	0.00251
Coating	205	399	0.00258
Coating	93	199	0.00273
Coating	23	73	0.00288

TABLE 4

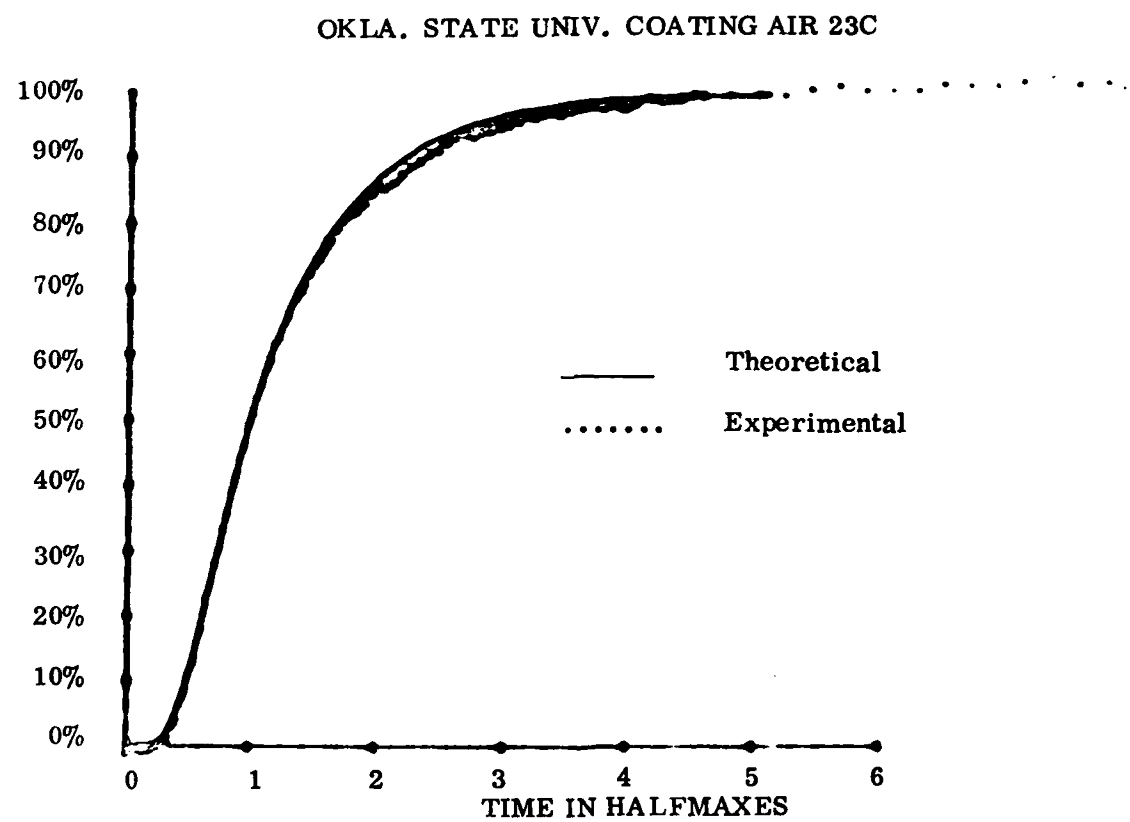
Specific Heat Results

Temp. (°K)	Temp. (°C)	Coating Run 1	Coating Run 2	Steel
350	77	0.51905	0.52145	0.47724
375	102	0.53324	0.54027	0.48175
400	127	0.54356	0.54995	0.49227
425	152	0.55271	0.56119	0.50173
450	177	0.56190	0.57115	0.50846
475	202	0.56759	0.57716	0.51875
500	227	0.57740	0.58447	0.52755
525	252	0.58942	0.59532	0.53683
550	277	0.60218	0.59873	0.54504
575	302	0.61699	0.60142	0.55349
600	327	0.63429	0.60287	0.56312
625	352	0.65684	0.60469	0.57390
650	377	0.68326	0.60510	0.58512
675	402	0.71580	0.60443	0.59739
700	427	0.75878	0.60494	0.60973
725	452	0.81170	0.60692	0.62316
750	477	0.85459	0.60988	0.63734
775	502	0.86087	0.61402	0.65170
800	527	0.86361	0.62104	0.66687
825	552	0.85323	0.63070	0.68309
850	577	0.80381	0.64010	0.70189
875	602	0.75636	0.64876	0.72623
900	627	0.72906	0.65818	0.75374
925	652	0.71783	0.66983	0.78855

TABLE 5

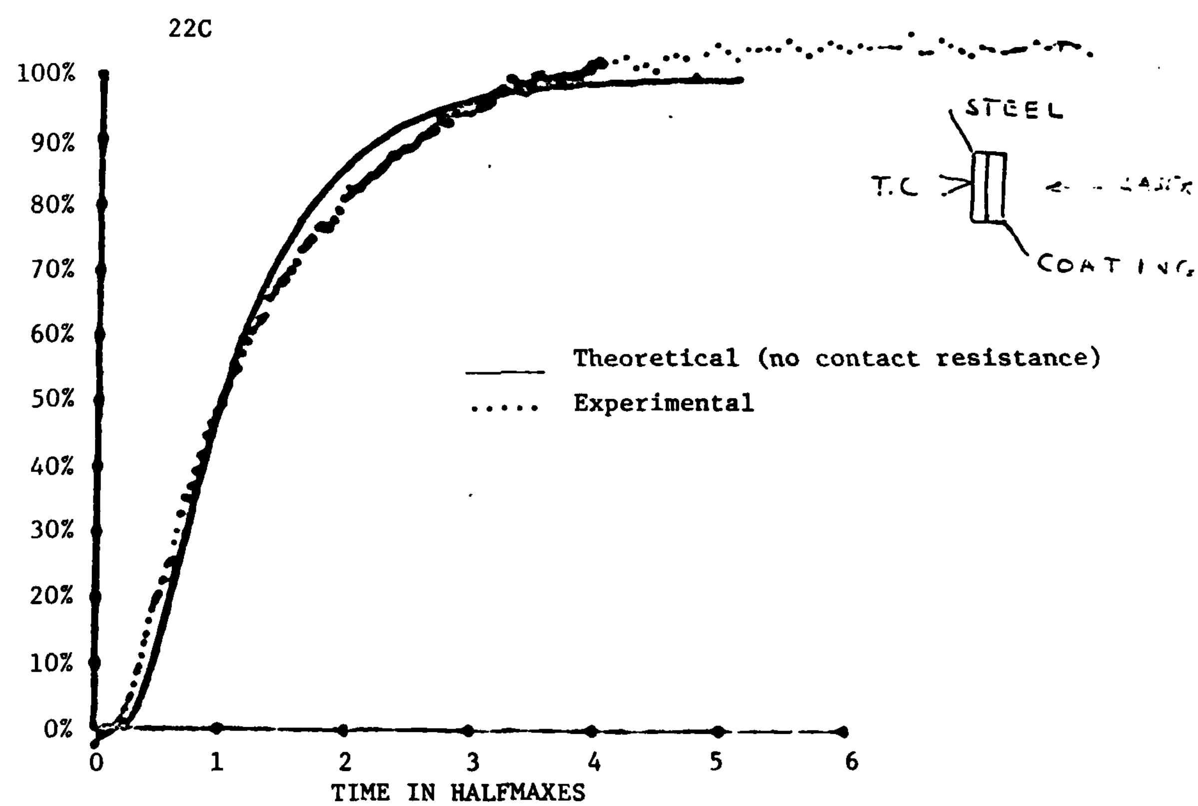
Thermal Conductivity Results

Temp. (°C)	Density (gm cm^{-3})	Specific Heat (W sec gm^{-1}K^{-1})	Diffusivity (cm^2 sec^{-1})	Conductivity (W cm^{-1}K^{-1})	Conductivity (BTU hr^{-1}ft^{-1}F^{-1})	Temp. (°F)
23	4.65	0.476	0.00320	0.00708	.405	73
93	4.65	0.530	0.00305	0.00752	.430	199
204	4.65	0.568	0.00290	0.00766	.438	399
537	4.65	0.624	0.00241	0.00699	.400	999
426	4.65	0.605	0.00244	0.00686	.392	799
315	4.65	0.602	0.00251	0.00703	.402	599
205	4.65	0.579	0.00258	0.00695	.397	399
93	4.65	0.536	0.00273	0.00680	.389	199
23	4.65	0.476	0.00288	0.00637	.364	73



HALFTIME	=	475289.9	MICROSECONDS	RUN ON 7/29/79
BASELINE	=	0.51312	VOLTS	UNFILTERED
THICKNESS	=	0.10460	CM	

Figure 1. Comparison of Experimental Rise Curve with Theoretical Model



HALFTIME = 1233102.0 MICROSECONDS RUN ON 7/29/79
BASELINE = 1.00100 VOLTS UNFILTERED
THICKNESS = 0.15113 CM

Figure 2. Rise Curve with Contact Resistance Between Layers

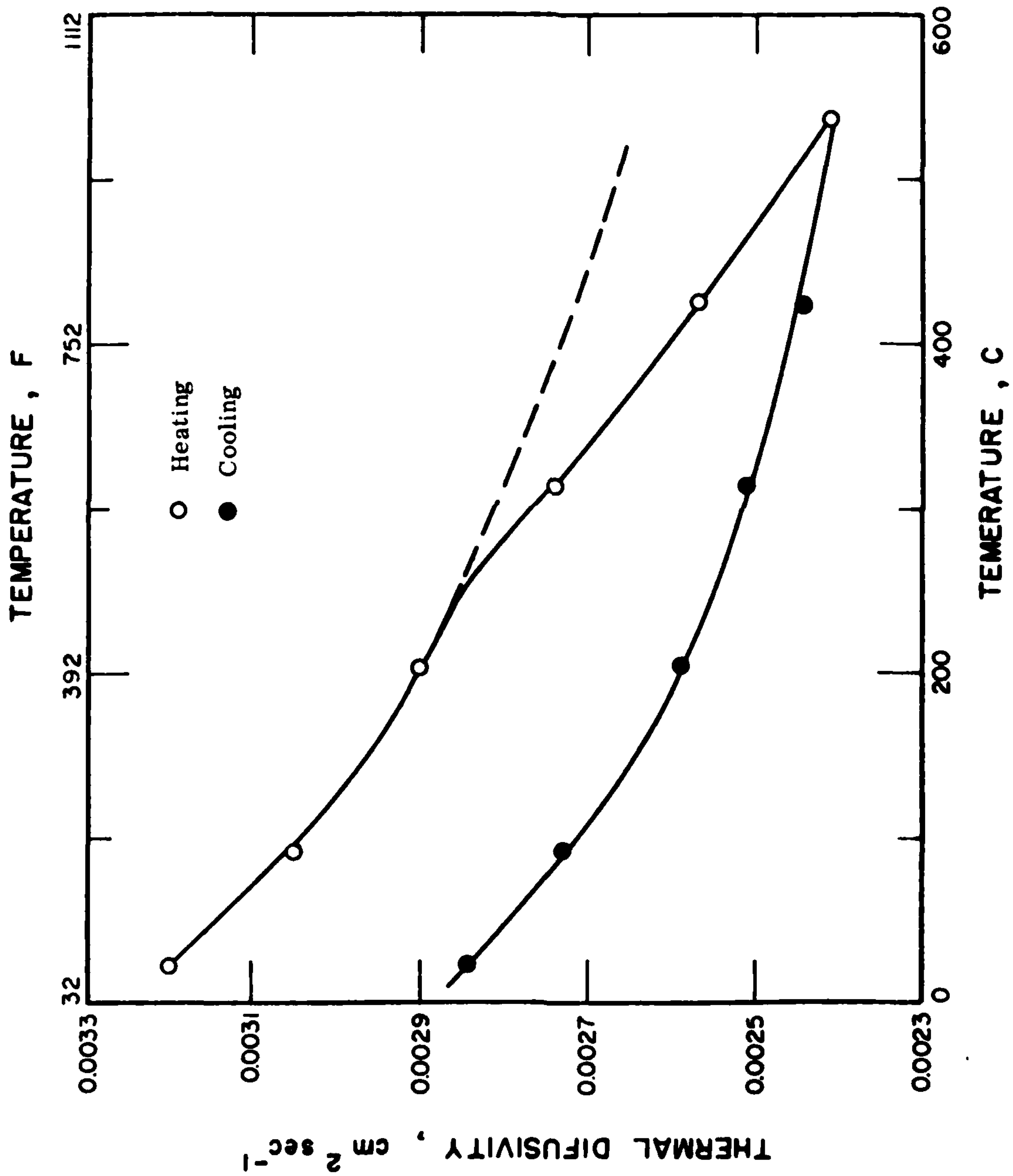


Figure 3. Thermal Diffusivity Results

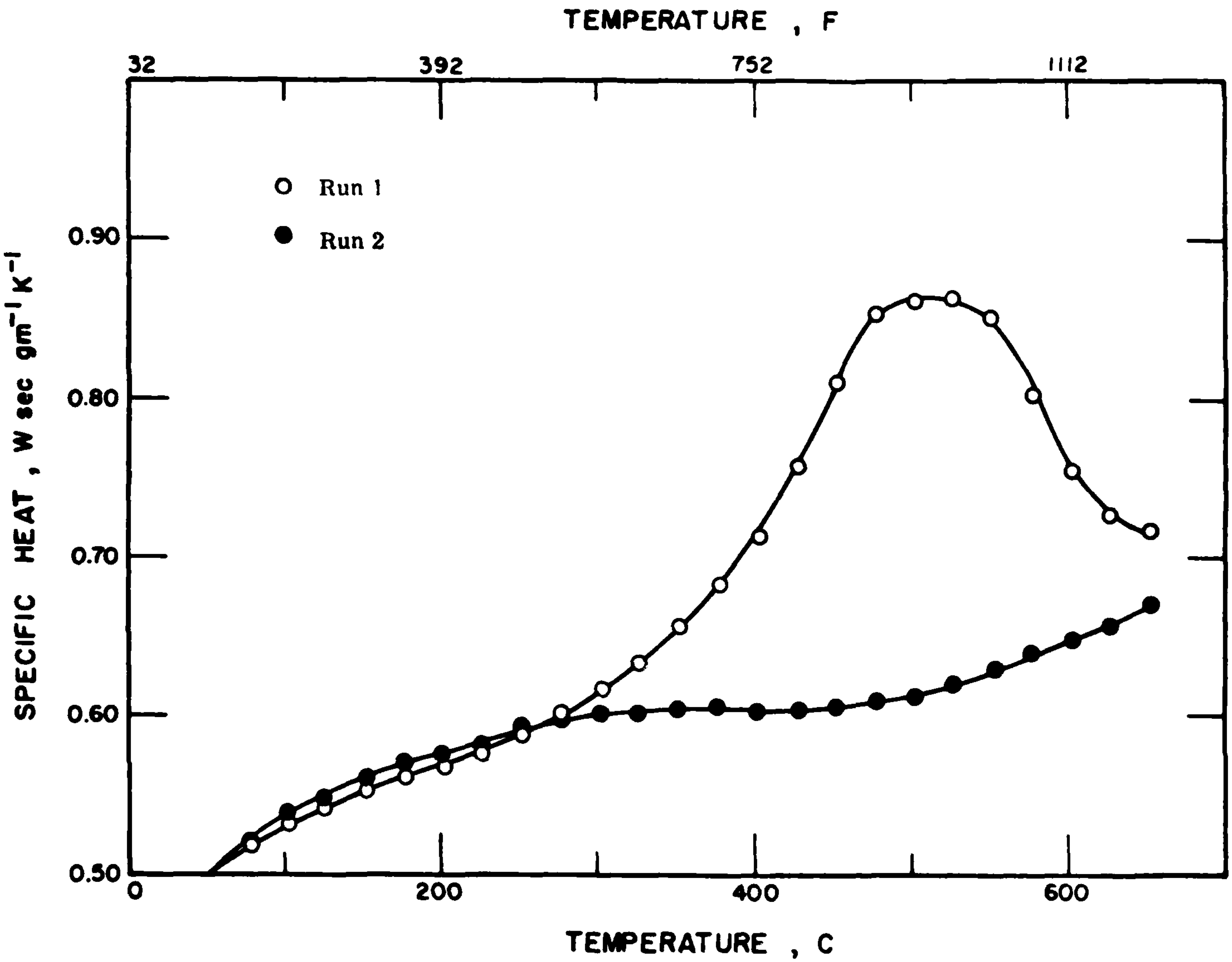


Figure 4. Specific Heat Results

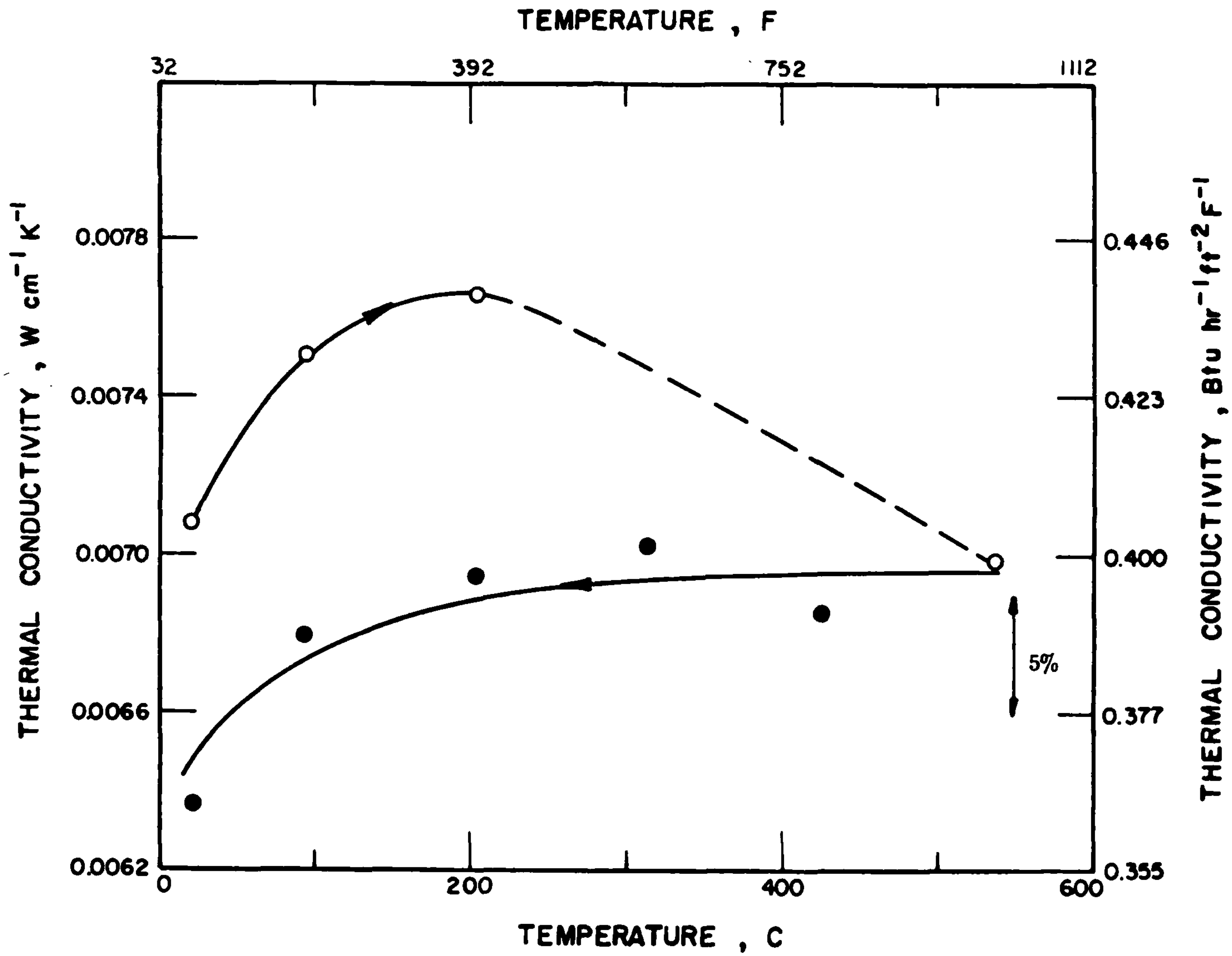


Figure 5. Thermal Conductivity Results

DATE
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